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Abstract:

Syros Island is worldwide known for its preservation of HP-LT parageneses in the Cycladic Blueschist Unit (CBU) providing one of the best case-studies to understand the tectonometamorphic evolution of a subduction channel. Conflicting structural interpretations have been proposed to explain the geological architecture of Syros, in part reflecting a lack of consensus about the tectonic structure of the CBU. In this study, the geological and tectonometamorphic maps of Syros have been entirely redrawn in order to decipher the structure of a fossilized subduction channel. Based on structural and petrological observations, the CBU has been subdivided into three subunits separated by major ductile shear zones. New observations of the Vari Unit confirm that it rests on top of the CBU through a detachment or exhumation fault. While retrograde top-to-the E/NE shearing overprinting prograde deformation is widespread across the island, the prograde deformation has been only locally preserved within the less retrograded units. We show that after the prograde top-to-the S/SW shearing deformation, the CBU was exhumed by an overall top-to-the E/NE shearing from the depth of the eclogite-facies all the way to the depth of the greenschist-facies and finally, to the brittle crust. The exhumation process encompassed the syn-orogenic stage (contemporaneous of subduction, within the subduction channel - Eocene) to the post-orogenic stage (contemporaneous with the formation of the Aegean Sea - Oligocene to Miocene). From syn-orogenic to post-orogenic exhumation, deformation progressively localized toward the base of the CBU, along large-scale ductile shear zones, allowing the preservation of earlier HP-LT structures and HP-LT metamorphic parageneses. Finally, this study brings new insights on the tectonometamorphic evolution of a subduction channel showing how strain localizes during the history of an accretionary complex, both during the prograde and retrograde history.

Keywords

Subduction channel; High-pressure low-temperature metamorphism; Strain localization; Ductile shear zone; Cycladic Blueschist Unit; Syros Island

Highlights

1) New geological and tectonometamorphic maps of Syros (Cyclades, Greece)

2) The Cycladic Blueschist Unit (CBU) was exhumed by an overall top-to-the east shearing

3) The CBU was exhumed as separate subunits with distinct P-T evolutions

4) Exhumation process encompassed syn- to post-orogenic stage

5) During exhumation, strain localized downward along major extensional shear zones

1) Introduction

High-pressure low-temperature (HP-LT) metamorphic rocks are generally attributed to former subduction zones. Intense retrograde deformation often overprints the early prograde events, but in some key-areas, the prograde and metamorphic peak deformation can provide insights on the tectonometamorphic history of a subduction zone (Alpine Corsica: Brunet et al., 2000; Vitale-Brovarone et al., 2011; Norwegian Caledonides: Austrheim and Griffin, 1985; Andersen et al., 1994; Labrousse et al., 2004; Terry and Heidelbach, 2006; Raimbourg et al., 2005; Himalaya: Burg et al., 1983; Liou et al., 2004; Epard and Steck, 2008; New Caledonia: Bell and Brothers, 1985; Aegean domain: Keiter et al., 2004, 2011; Philippon et al., 2011).

The Aegean domain and specifically the Cyclades Archipelago, form a natural laboratory for studying a former subduction zone. Syros Island, located in the central part of the Cyclades (Fig. 1a), is worldwide known for its spectacular preservation of deformed HP-LT metamorphic rocks such as eclogites and is considered to be the type locality of glaucophane (Hausmann, 1845). Rocks of this island have been the focus of many petrological, geochronological and structural studies, leading to different interpretations regarding: 1) the overall geometry of the CBU, 2) metamorphic peak conditions and 3) the role of major tectonic contacts (Fig. 1b; Trotet et al., 2001a, 2001b; Rosenbaum et al., 2002; Ring et al., 2003; Keiter et al., 2004, 2011; Schumacher et al., 2008; Philippon et al., 2011; Soukis and Stöckli, 2013). Despite excellent outcropping conditions, these differences are sometimes drastic, thus hindering our understanding of this classical example of a fossilized subduction channel.

This paper focuses on the tectonometamorphic evolution of the Cycladic Blueschist Unit. New maps and profiles are here further discussed in terms of their situation within the subduction channel. We demonstrate a progressive top-to-the E/NE continuum of deformation from eclogite- to greenschist-facies. Most of the deformation completely overprinted the prograde subduction-related deformation. However, we highlight areas where syn-burial tectonometamorphic features are preserved. In addition, we confirm the existence of the Vari Detachment recently challenged by Philippon et al. (2011) as an extensional detachment partly responsible for the exhumation of the CBU. Finally, deep-seated subduction processes are then discussed in the framework of the Hellenic subduction zone.

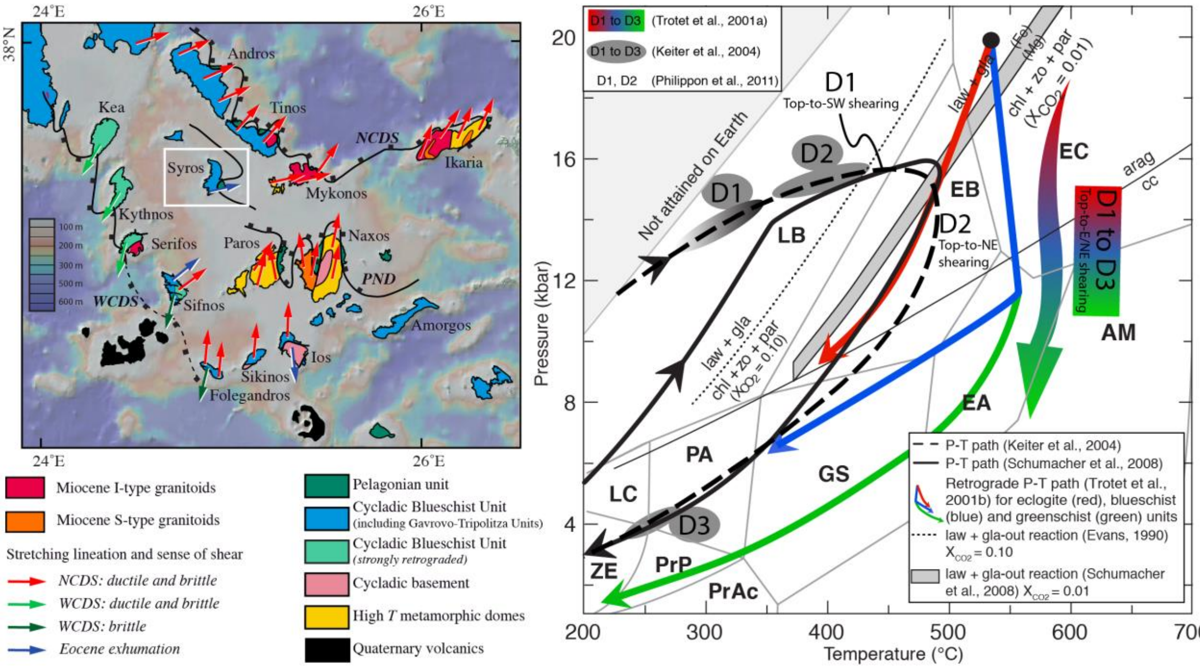


Figure 1: Localization of the studied area and Pressure-Temperature-deformation paths of Syros available in literature. a) Tectonic map of the Cyclades showing the major tectonic structures such as the North Cycladic Detachment System (NCDS), the West Cycladic Detachment System (WCDS) and the Paros-Naxos Detachment (PND), as well as kinematic indicators, after Jolivet et al. (2015). b) Representation of the different calculated P-T paths for the CBU in Syros. D1, D2 and D3 phases of deformation after Trotet et al. (2001a, 2001b), Keiter et al. (2004), Philippon et al. (2011) highlight the conflicting prograde or retrograde interpretations of the main deformation observed on Syros. Facies: AM, amphibolite; EA, epidote-amphibolite; EB, epidote-blueschist; EC, eclogite; GS, greenschist; LB, lawsonite-blueschist; LC, lawsonite-chlorite; PA, pumpellyite-actinolite; PrAc, prehnite-actinolite; PrP, prehnite-pumpellyite; ZE, zeolite (after Peacock, 1993). Lawsonite + glaucophane-out reactions after Evans (1990) and Schümacher et al. (2008).

2) Geological setting

2.1) Tectonometamorphic evolution of the Cycladic Blueschist Unit

The Aegean domain, part of the eastern Mediterranean Sea, experienced a two steps tectonometamorphic evolution. Firstly, the late Cretaceous-Eocene formation of the Hellenides-Taurides chain resulted from the subduction and collision of the Apulian microcontinent with Eurasia (Bonneau and Kienast, 1982; Dercourt et al., 1986; van Hinsbergen et al., 2005). The entrance of the Apulian crust in the subduction zone led to an episode of crustal thickening and syn-orogenic exhumation of HP-LT metamorphic units such as the Cycladic Blueschist Unit (CBU; Fig. 1a; Blake et al., 1981; Bonneau and Kienast, 1982; Jolivet et al., 2003, 2004; Brun and Faccenna, 2008; Jolivet and Brun, 2010; Ring et al., 2010). Secondly, post-orogenic extension in the Rhodope from 45 Ma and in the Aegean Sea from 35 Ma was associated with the retreat of the African slab (Jolivet and Faccenna, 2000; Brun and Sokoutis, 2010; Jolivet and Brun, 2010; Ring et al., 2010). In the Aegean domain, part of western Anatolia and in the Rhodope Massif, back-arc extension of the previously thickened crust was accommodated by several regional-scale detachments such as the North Cycladic Detachment System (NCDS) or the West Cycladic Detachment System (WCDS) (Fig. 1a; Jolivet et al., 2010; Grasemann et al., 2012).

Located in the center of the Aegean domain, the Cyclades correspond to the deepest exhumed parts of the Hellenides-Taurides chain and are mainly composed by the CBU (Fig. 1a). This unit is mainly made of marbles, metapelites and metabasites all showing peak P-T conditions in the blueschist- or eclogite-facies (Blake et al., 1981; Bonneau, 1984; Okrush and Bröcker, 1990; Avigad and Garfunkel, 1991; Trotet et al., 2001b; Schumacher et al., 2008). The CBU experienced alpine tectonic and metamorphic evolution, with an early burial in HP-

LT conditions reaching ~18-20 kbar and 500-550 °C (Fig. 1b; Dürr et al., 1978; Bröcker and Enders, 2001; Trotet et al., 2001b; Parra et al., 2002; Tomaschek et al., 2003; Augier et al., 2015) during the Eocene (~50-35 Ma; Tomaschek et al., 2003; Putlitz et al., 2005; Lagos et al., 2007). During the Oligocene and for the whole Miocene, this event was followed by LP-HT greenschist- to amphibolite-facies overprint of variable intensity (Fig. 1a; Altherr et al., 1979, 1982; Wijbrans and McDougall, 1986; Buick, 1991; Keay et al., 2001; Vanderhaeghe, 2004; Duchêne et al., 2006; Bröcker et al., 2013; Beaudoin et al., 2015). On top of the CBU, the Upper Cycladic Unit (UCU) corresponds to the uppermost parts of the nappe stack. The UCU is composed of Permian to Mesozoic metasediments, minor orthogneisses and ophiolites equilibrated in greenschist- to amphibolite-facies metamorphic conditions during the Cretaceous, sometimes covered with Oligocene to Miocene sediments (Sanchez-Gomez et al., 2002; Kuhlemann et al., 2004; Lecomte et al., 2010; Menant et al., 2013). Structurally below the CBU, the Cycladic Continental Basement (CCB) crops out as large-scale tectonic windows on several islands in the central and southern part of the Cyclades (Fig. 1a; e.g. Paros, Naxos, Ios or Sikinos; Andriessen et al., 1987). This unit is composed of Variscan orthogneisses enveloped by metasediments that locally retain metamorphic relics of amphibolite-facies assemblages suggesting a complex pre-alpine history (Bonneau and Kienast, 1982; Andriessen et al., 1987; Keay, 1998; Photiades and Keay, 2003; Gupta and Bickle, 2004; Huet et al., 2009; Augier et al., 2015). Late exhumation stages of both the CBU and the CCB were accompanied by emplacement of syn-tectonic Miocene intrusions (i.e. Tinos, Mykonos, Ikaria, Naxos, Serifos, Lavrio; Fig. 1a; Jansen, 1973; Altherr et al., 1982; Faure et al., 1991; Lee and Lister, 1992; Altherr and Siebel, 2002; Pe-Piper et al., 2002; Grasemann and Petrakakis, 2007; Iglseder et al., 2009; Bolhar et al., 2010; Lecomte et al., 2010; Stouraiti et al., 2010; Denèle et al., 2011; Laurent et al., 2015; Rabillard et al., 2015).

2.2) Geology of Syros

Located in the central part of the Aegean domain, Syros is mainly composed by the CBU except for the Vari Unit (Fig. 2a). Vari Unit, composed of greenschist mylonites and orthogneiss, corresponds to a distinct tectonic unit attributed to UCU, separated from the CBU by the Vari Detachment (Trotet et al., 2001a; Keiter et al., 2004, 2011; Soukis and Stöckli, 2013). The basal part of the CBU crops out in the southwestern part of the island and is mainly composed of albitic micaschists and rare gneisses (e.g. the Komito gneiss; Fig. 2a; Hecht, 1985). Structurally above, the central part of Syros is dominated by alternating sequences of marble and micaschist layers (Fig. 2a). In this area, metabasites are a minor component and often occur as dismembered boudins intercalated within the metamorphic series. Conversely, in other parts of the island and especially in the north, metabasites form the dominant lithology and often occur as kilometer-scale massive bodies (e.g. Hecht, 1985; Keiter et al., 2004, 2011; Philippon et al., 2011). Metabasites are locally turned into massive eclogite-facies rocks but also occur as blueschist- or greenschist-facies rocks (Trotet et al., 2001a).

2.3) Pressure-Temperature-time evolution

Petrological studies yielded contrasting estimates for metamorphic peak conditions from 15-16 kbar and 500°C (Schliestedt et al., 1987; Okrusch and Bröcker, 1990; Avigad and Garfunkel, 1991; Schmädicke and Will, 2003; Schumacher et al., 2008) to 19-20 kbar and 525-550°C (Fig. 1b; Trotet et al., 2001b; Groppo et al., 2009; Dragovic et al., 2012; Ashley et al., 2014). Timing and duration of this subduction-related P-T evolution have been quite well constrained since the 1980s, using a large panel of isotopic systems such as K-Ar, $^{40}Ar/^{39}Ar$, Rb-Sr, U-Pb, Lu-Hf, Sm-Nd systems on various minerals (Fig. 2b; Altherr et al., 1979, 1982; Andriessen et al., 1979; Wijbrans and McDougall, 1986; Maluski et al., 1987; Wijbrans et al., 1990; Bröcker et al., 1993, 2013; Bröcker and Franz, 1998, 2006; Bröcker and Enders, 1999; Tomaschek et al., 2003; Putlitz et al., 2005; Lagos et al., 2007; Huet, 2010; Dragovic et al., 2012). Studies attempting to date the burial culmination led to ca. 53-49 Ma ages (Tomaschek et al., 2003; Putlitz et al., 2005; Lagos et al., 2007). Then, the retrogression in the greenschist-facies has been dated between 25 and 21 Ma (Bröcker et al., 2013). Final exhumation stages of the CBU were recently constrained by low-temperature thermochronological tools between 12 and 8 Ma (Fig. 2b; Ring et al., 2003; Soukis and Stöckli, 2013).

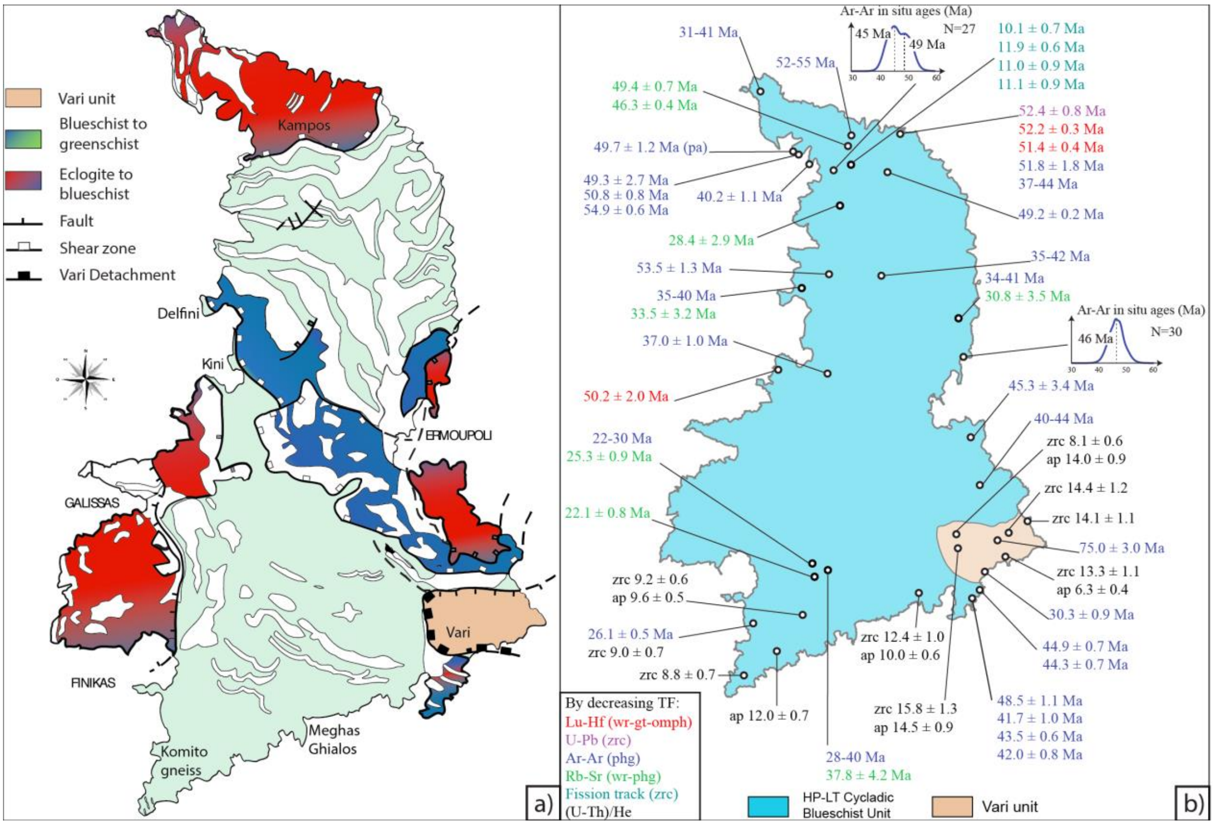


Figure 2: Previous geological and geochronological works on Syros. a) Metamorphic map of Syros showing the main tectonic structures, after Trotet et al. (2001a). b) Compilation of previous geochronological data calculated after U-Pb (Bröcker & Enders, 1999; Tomaschek, et al., 2003), Lu-Hf (Lagos, et al., 2007), $^{40}Ar/^{39}Ar$ (Maluski et al., 1987; Tomaschek, et al., 2003; Putlitz et al., 2005; Huet, 2010; Bröcker et al., 2013), Rb-Sr (Bröcker & Enders, 2001; Bröcker et al., 2013), (U-Th)/He (Soukis and Stöckli, 2013) and fission track methods (Ring et al., 2003).

2.4) Main controversies

The relative importance of the prograde and retrograde deformations, compression *vs* extension, syn-orogenic *vs* post-orogenic exhumation is still debated. Hecht (1985) elaborated the geological map of Syros at the scale 1: 50000 and interpreted all basal contacts of metabasites as tectonic, mostly as thrusts, contradicting the initial interpretation of metabasite occurences as olistoliths within a flysch sequence (Bonneau et al., 1980a, 1980b; Blake et al., 1981). Recently, Keiter et al. (2011) remapped the entire island at the scale 1: 25000. These authors argued that an important result of their study is the identification of a significant late brittle deformation on Syros that was so far poorly constrained. In parallel, Philippon et al. (2011) reinterpreted the geological map of Syros, based on the original map of Hecht (1985). These authors disconfirmed the existence of the Vari Detachment, correlating the Vari and Komito gneisses and repositioning the Vari Unit at the base of the CBU. Soukis and Stöckli (2013) challenged this conclusion, restoring the original interpretation of Gautier (1995), Trotet et al. (2001a) or Ring et al. (2003), thus recognizing the juxtaposition of the Vari Unit onto the CBU by the Vari Detachment. A second controversy relates to the regional and tectonic significance of the deformation recorded by HP-LT rocks. According to Trotet et al. (2001a), the main deformation phase is retrograde and was acquired during exhumation of the CBU from eclogite- to greenschist-facies (D1 to D3; Fig. 1b). For these authors, exhumation occurred during a continuum of top-to-the E/NE shearing deformation from the early Eocene (syn-orogenic exhumation) to the early Miocene (post-orogenic exhumation). In contrast, Keiter et al. (2004, 2011) interpreted the main deformation event affecting the CBU as prograde, implying therefore a rigid body exhumation of the whole structure (D1 to D3; Fig. 1b). Finally, Philippon et al. (2011) describe two distinct ductile phases of deformation (Fig.

1b), i) a first top-to-the SW prograde deformation (D1) and, ii) a second extensional top-to-the NE penetrative shear (D2) affecting the entire CBU.

As long as these discrepancies are not addressed, the deep processes and long-term evolution of the CBU in the subduction channel will remain poorly understood.

3) A new geological map of Syros

3.1) Method and mapping technique

In order to complement existing geological maps and put constraints on the geometry of Syros, the whole island has been remapped based on field observations and satellite-images interpretation (Fig. 3). Lithology and tectonic boundaries have been redrawn following our observations all over the island. For mutual comparison, the color code of the legend is the same as in the geological map of Keiter et al. (2011), with simplified lithologic subdivisions for the purpose of our tectonometamorphic study. Calcitic and dolomitic marbles were merged together into a unique metacarbonate comprehensive unit. Similarly, further subdivisions within the mafic protoliths were abandoned. Anyway, principal occurrences of serpentinite and eclogite are reported on the map (Fig. 3). Additionally, the finite strain markers were studied as well as the link with the metamorphic record. Results are given on figure 3.

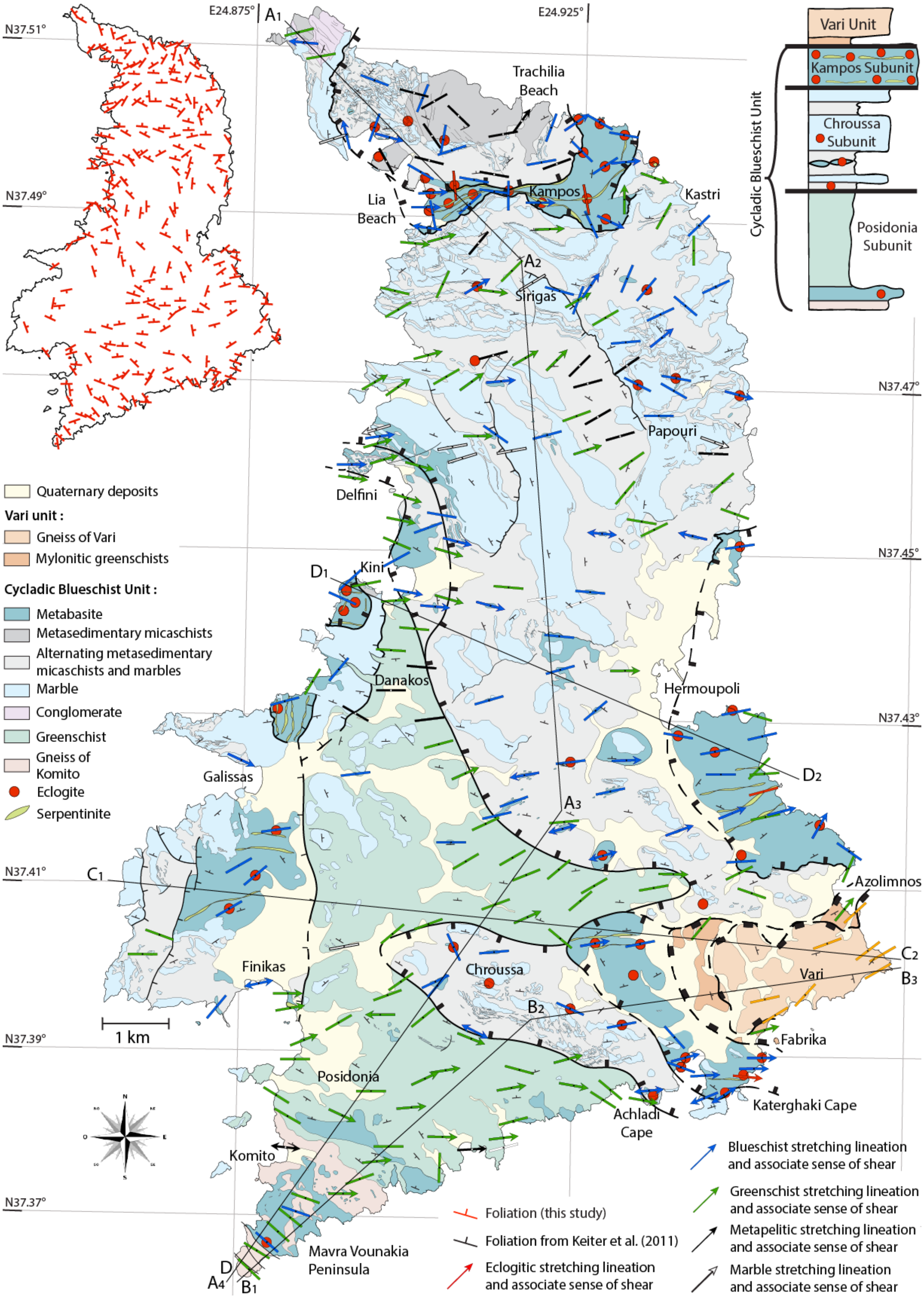
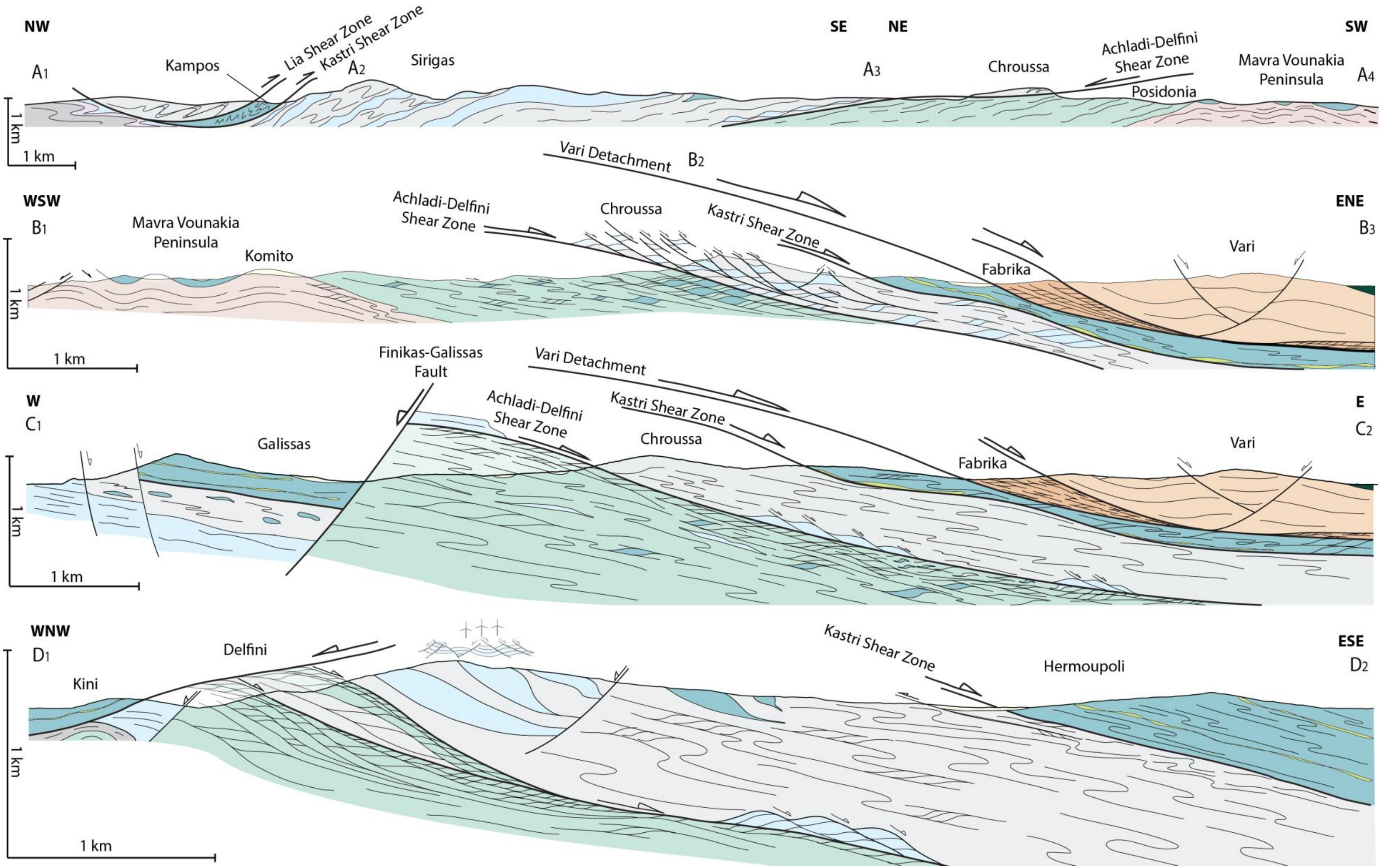


Figure 3: New geological map of Syros showing the main tectonic structures and lithologic distributions (geometry of the Vari Unit after Soukis and Stöckli, 2013). Cross-sections are traced with black lines and highlight the architecture of Syros. Planar (foliation planes) and linear (stretching lineations) fabrics are represented with their associated metamorphic facies. Also shown are the localities cited in the text.



242
243 Figure 3 (continue)

3.2) Large-scale structure

From a lithological point of view, our new geological map does not significantly differ from the one of Keiter et al. (2011) with only few areas where minor changes are reported; the map thus seems relatively robust. As examples of differences, we highlight larger outcrops of metabasites in several parts of the island, like in Mavra Vounakia peninsula or near the Delfini Bay (Fig. 3).

The most obvious changes are related to the structural aspects in a broad sense, and particularly the way the metamorphic sequence is structured in coherent units. Our approach consisted first in the identification of high strain zones (i.e. major shear zones) where deformation is concentrated, and second, in the recognition of subunits characterized by their lithological content and metamorphic record. This mapping approach allows us redefining the stack of the CBU, subdividing it in three subunits delimited by major shear zones, which are from bottom to top:

1) Posidonia Subunit, which is lithologically subdivided in two parts: the structurally lower felsic gneiss of Komito with intercalated boudins of metabasite, overlain by albitic micaschists, few metabasites and thin marble layers (Fig. 3). The entire basal unit has been overprinted in the greenschist-facies with only few areas preserving high-pressure relics in centimeter-scale mafic boudins (Fig. 3). The Achladi-Delfini Shear Zone delimits the Posidonia Subunit from the upper Chroussa Subunit.

2) Chroussa Subunit, which is composed of a lithostratigraphic sequence of alternating micaschists, thick marble layers and metabasites (Fig. 3). Although some areas are more overprinted in the greenschist-facies, blueschist-facies parageneses are well preserved in this subunit. Fresh eclogites are sometimes preserved in the core of metabasic boudins of any scale (Fig. 3). The Kastri Shear Zone delimits the Chroussa Subunit from the upper Kampos

Subunit.

3) Kampos Subunit, which is mainly composed of a mélange of metabasites, including metagabbros, metabasalts, and locally still visible remains of metapillow-lavas (see Keiter et al., 2011 for details) wrapped by strongly foliated metapelites and/or serpentinites. Within this subunit, eclogite- and blueschist-facies parageneses are preserved, with only few narrow zones overprinted in the greenschist-facies (Fig. 3). The Vari Detachment delimits the top of Kampos Subunit, and at larger scale the entire CBU, from the upper Vari Unit.

Finally, the Vari Unit is formed from bottom to top by a greenschist mylonitic unit and the gneiss of Vari intruding amphibolite-facies metabasites (see also Soukis and Stöckli, 2013). High-pressure rocks were not recognized in the Vari Unit.

4) Deformation and metamorphic record in the CBU

Finite strain markers were studied throughout the island. In parallel, physical conditions of the deformation were evaluated by the recognition of syn-kinematic minerals in metabasites and other types of lithologies. All three subunits experienced HP-LT imprint in the eclogite-facies conditions. This initial record is however unevenly distributed. In this section we explore the relationships between the preservation/retrogression of HP-LT parageneses and the relative intensity of deformation.

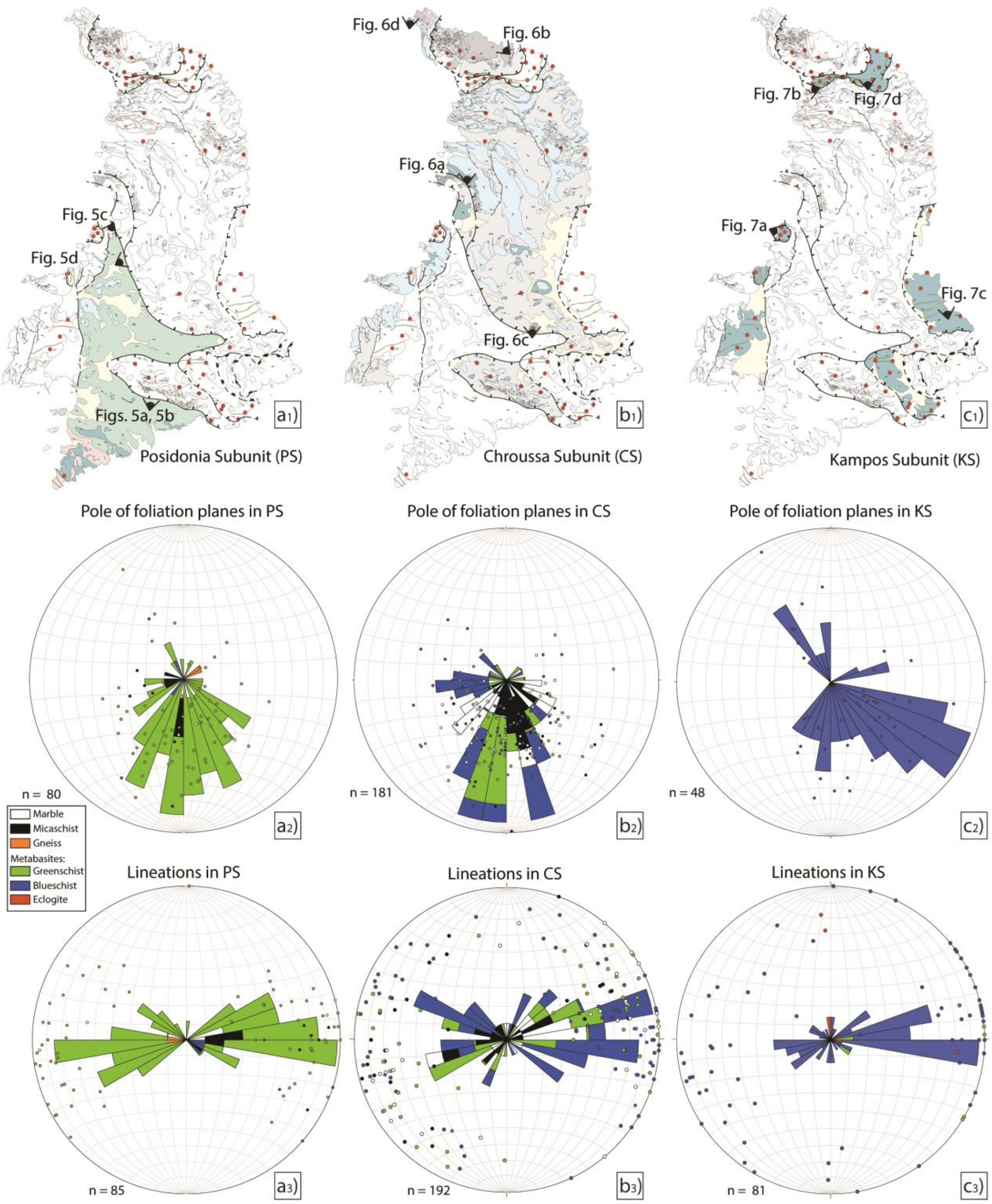


Figure 4: Stereograms of the planar and linear fabric measured on Syros and their associated metamorphic facies or lithology if mineralogy does not allow identifying the metamorphic-facies. a_1, b_1, c_1) Geological maps highlighting respectively the Posidonia, Chroussa and Kampos subunits and localizing the pictures displayed on the figures 5, 6 and 7. a_2, b_2, c_2) Rose diagram of the poles of foliation planes in each subunit. a_3, b_3, c_3) Rose diagram of stretching lineations in each subunit.

4.1) Posidonia Subunit

Foliation in Posidonia Subunit dips shallowly toward NNW to NNE (Fig. 4a). A syn-greenschist facies stretching lineation is observed almost systematically, marked by the stretching of syn-kinematic chlorite and/or albite in rocks showing only greenschist parageneses (Fig. 4a). Syn-blueschist lineations were observed in only four outcrops (Fig. 3). For each of these areas, HP-LT markers are preserved within up to a few meters thick mafic to ultra-mafic boudins hosted in greenschist-facies rocks. The trend of stretching lineations varies between N60°E to N100°E with a dominant E-W orientation (Fig. 4a). Foliation planes and stretching lineations measured in the Mavra Vounakia Peninsula (Fig. 3) are slightly different from those observed in the rest of Posidonia Subunit. There, foliation planes measured in gneiss and metabasites are NW-SE trending with oscillating dip direction toward the NE or SW and carried stretching lineations oriented between N120°E and N140°E (Fig. 3).

In Posidonia Subunit, markers of non-coaxial ductile deformation are observed as shear bands, sigma-clast systems, drag folds or asymmetric boudinage. For more than 90% of visited outcrops, these markers indicate a consistent syn-greenschist top-to-the east sense of shear (Figs. 3, 5a, 5b). Additionally, the rocks of Posidonia Subunit are tightly to isoclinally folded, with fold axes either parallel or perpendicular to the stretching direction (Figs. 5c, 5d).

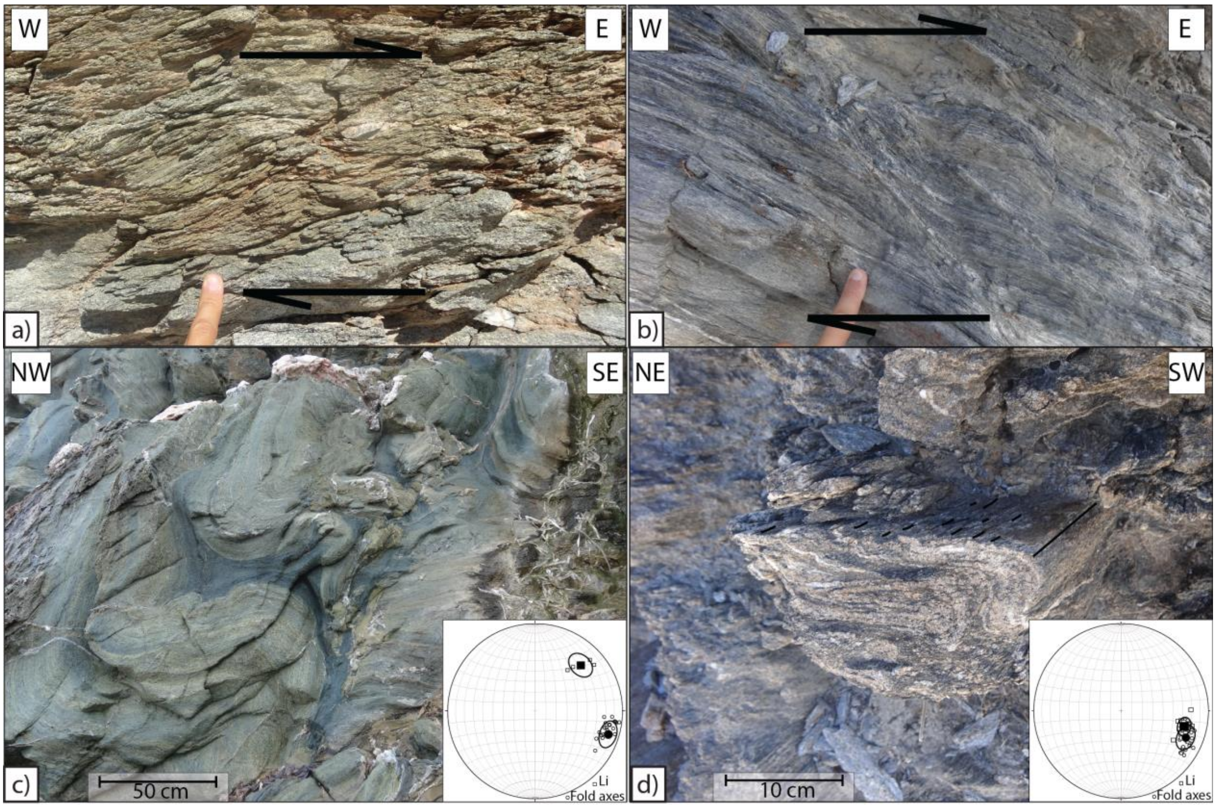


Figure 5: Syn-greenschist top-to-the east shearing characterizing the Posidonia Subunit. Localization of pictures is showing on figure $4a_1$. a, b) Syn-greenschist top-to-the east shear bands (GPS coordinate: 37°23’16.2’’ / 24°54’21.5’’) c) Greenschist folds characterized by orthogonal fold axes compared to syn-greenschist stretching lineations (GPS coordinate: 37°26’40.5’’ / 24°53’53.8’’). Data are plotted on the stereogram. d) Parallel fold axes and syn-greenschist stretching lineations observed in the contact zone with the Chroussa Subunit near the village of Danakos (GPS coordinate: 37°26’06’’ / 24°54’05.1’’). Data are plotted on lower hemisphere stereograms.

4.2) Chroussa Subunit

Chroussa Subunit consists of a succession of marble layers, micaschists and metabasites, showing both syn-blueschist and syn-greenschist deformation (Fig. 4b). Measured foliation planes shallowly dip to north (Fig. 4b) with local variations. Within blueschist-facies rocks, a group of N-S striking foliation planes dips eastward (Fig. 4b). Two other orientations of foliation planes were measured in marbles, dipping toward the NE or the NW (Fig. 4b). As for Posidonia Subunit, only a few foliation planes dip southward. The planar fabric observed in Chroussa Subunit is often associated with a stretching lineation marked by glaucophanes needles in blueschist-facies rocks and chlorite and/or albite pods in greenschist-facies rocks (Fig. 4b). Overall, the bulk of measured stretching lineations shows a constant orientation with a rather low dispersion between N70°E and N100°E. A subordinate N20°E set of lineations is observed in blueschist-facies rocks (Fig. 4b).

Rocks of Chroussa Subunit are strongly deformed at all scales. Markers of non-coaxial ductile deformation are similar to those observed in Posidonia Subunit. Likewise, this subunit shows top-to-the E/NE ductile deformation for both syn-blueschist and syn-greenschist markers (Figs. 6a, 6b, 6c). In the northern part of Syros, near Trachilia Beach, top-to-the northeast shear bands affecting lawsonite pseudomorphs in metapelites occur (Fig. 6b). In few places, we observed in the Chroussa Subunit shear bands or asymmetric boudinage showing retrograde top-to-the west deformation (Figs. 3, 6c). Folds are also common in Chroussa Subunit showing curved axes locally parallel to the stretching lineation and axial closures like in sheath folds (Fig. 6d).

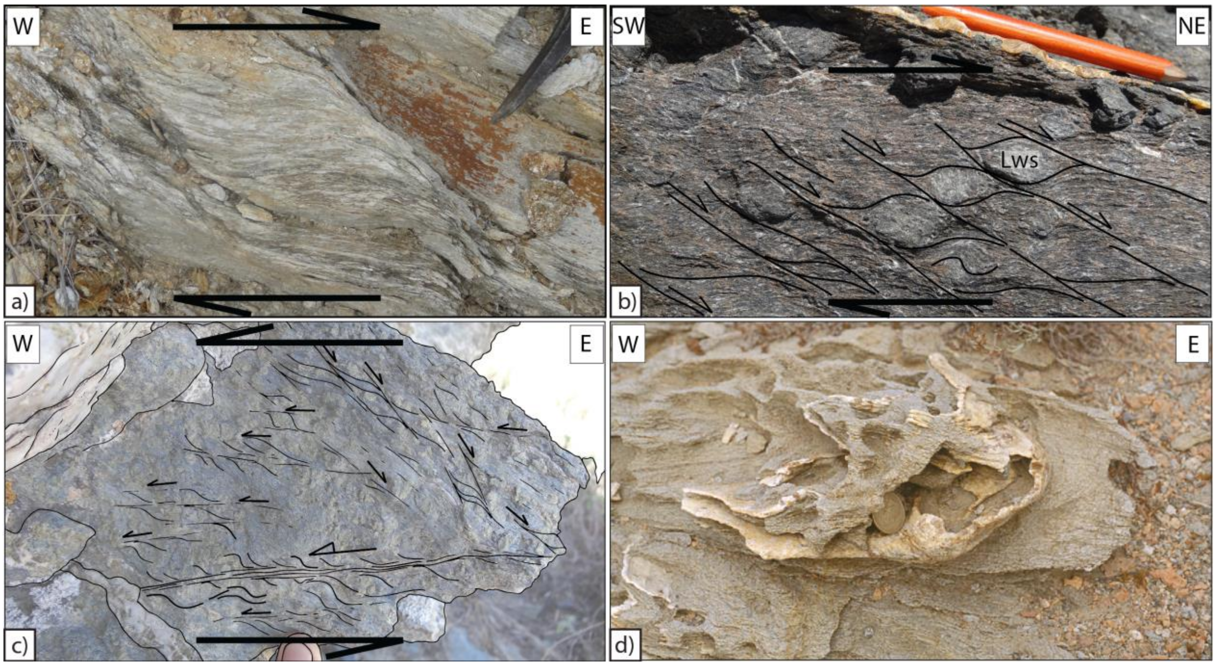


Figure 6: Shearing criteria observed in Chroussa Subunit. Outcrop location is shown on figure 4a$_2$. a) Syn-greenschist top-to-the east shear bands (GPS coordinate: 37°28'24.1'' / 24°55'11.6''). b) Top-to-the northeast shear bands affecting preserved pseudomorphs of lawsonite (GPS coordinate: 37°30'07.9'' / 24°54'54.4''). c) Retrograde top-to-the west shearing observed locally in the Chroussa Subunit (GPS coordinate: 37°24'49.3'' / 24°55'45.5''). The steep shear planes are secondary shear zones rotating top west with an antithetic sense of shear. d) Curved axis fold observed in micaschists, sub-parallel to the stretching lineation and showing closure typical of sheath fold (GPS coordinate: 37°30'39.4'' / 24°52'39.3'').

4.3) Kampos Subunit

Kampos Subunit displays rocks equilibrated in eclogite- and blueschist-facies. Foliation planes dip toward north or northwest (Fig. 4c). Stretching lineations are mainly oriented between N70°E and N100°E and dominantly marked by elongated glaucophane minerals along a main stretching direction (Fig. 4c). N-S syn-blueschist stretching lineations are common in the metabasites near Kampos village (Figs. 3, 4c). In some outcrops (e.g. Kini, Kampos or near the airport), metabasite bodies show only incipient deformation with preserved metapillow-lavas or metabasaltic dykes crosscutting metagabbros (Fig. 7a). Conversely, in others outcrops, rocks experienced intense top-to-the-east shearing recorded during retrogression of eclogites in blueschist-facies conditions (Fig. 7). This characteristic top-to-the east ductile deformation increases up-section toward the contact with Vari Unit, defining a single strain gradient accompanied by a gradient of eclogite retrogression.

Figure 7: Intense syn-eclogite to blueschist-facies deformation of Kampos Subunit illustrating top-to-the east sense of shear. Localization of pictures is showing on figure 4a$_3$. a) Metabasaltic dyke cross-cutting a massive metagabbro unit showing no deformation (GPS coordinate: 37°26'43.6'' / 24°53'20.4''). b) Isoclinal folds characterized by sub-horizontal axes parallel to the stretching lineation. These folds show intense thinning during shearing with pure shear component during deformation (GPS coordinate: 37°29'19.2'' / 24°54'03.4''). c, d) Syn-blueschist top-to-the east shearing affecting high-pressure metabasites (GPS coordinate: c) 37°25'05.3'' / 24°57'42.9'' d) 37°29'22.6'' / 24°55'42.1'').

4.4) Brittle deformation

Ductile features are affected by late, sometime pervasive, brittle deformation recorded in all units by both low and high-angle normal faults. These normal faults are well exposed near Sirigas where they offset two large boudinaged marble layers (Fig. 8a). Two normal faults, occurring between Sirigas and Papouri and close to Kini, reach the critical size to be followed at map scale (Fig. 3). Near Galissas (see location on Fig. 8b), the strongly retrogressed rocks of Posidonia Subunit are in contact with the HP-LT blueschist- and eclogite-facies metabasites of Kampos Subunit (Figs. 3, 8b). Quaternary slope deposits cover this contact. Along the road between Finikas and Galissas, a west-dipping fault zone with cataclasites and striations crops out for about 50 m-long, showing oblique normal kinematics with top-to-the W-SW sense of movement (Figs. 8b, 8c, 8d, 8e). On top of this fault plane, a 3-4 m-thick brittle fault gouge is observed. Moreover, south of Finikas, we observed normal faults trending N-S with similar top-to-the southwest kinematics (Fig. 8b, 8f). These two outcrops characterize a 4 km-long late brittle normal fault, the Finikas-Galissas Fault (Figs. 3, 8b).

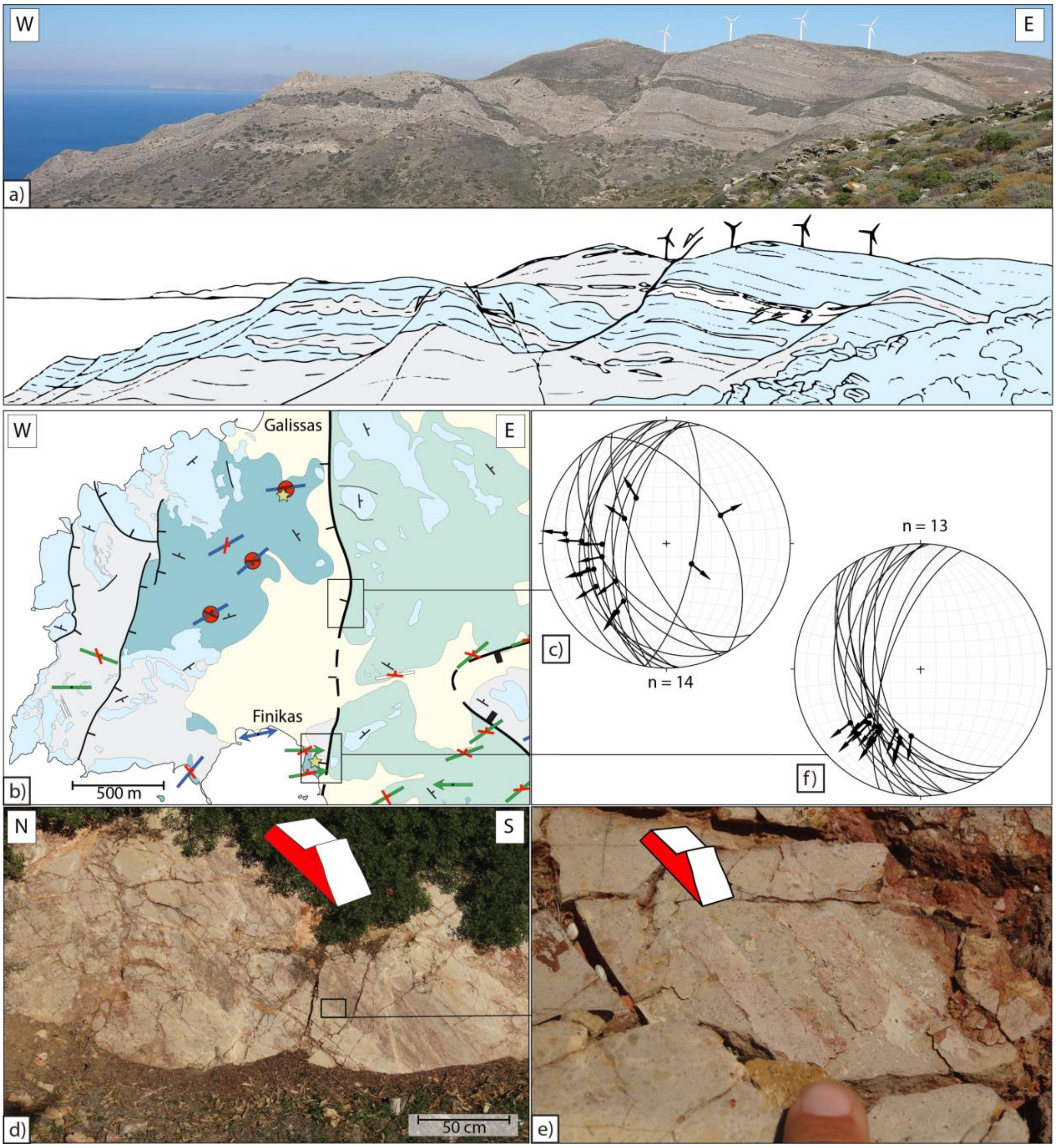


Figure 8: Field photographs of observed brittle normal faults. a) Panorama (Chroussa Subunit) showing coeval top-to-the east and west ductile-brittle to purely brittle normal faults. b) Zoom of the geological map showing location of outcrops along the Finikas-Galissas Fault. c) Associated stereogram showing measured brittle normal fault planes that indicate top-to-the W/SW kinematic. d) Brittle fault plane observed along the main road between Finikas and Galissas. e) Zoom on the striated fault plane showing the normal sense of motion. f) Stereogram showing brittle normal fault planes measured near Finikas village that indicate top-to-the southwest kinematic.

5) Geometry, kinematics and metamorphic conditions of the major contacts

If the Vari Detachment has already been described in previous works (Soukis and Stöckli, 2013), some of the major contacts described below were so far either neglected (i.e. Achladi-Delfini Shear Zone), or not fully understood in previous works. The new map, supported by field data and satellite observation, allows us to identify their main characteristics and role in the island overall architecture.

5.1) Posidonia-Chroussa subunits contact: the Achladi-Delfini Shear Zone

The Posidonia-Chroussa subunits contact is exposed between Achladi Cape and Delfini (Fig. 9, see location on Fig. 3). In its southern limit, the trace of the shear zone can be followed over more than 3 km in the landscape, shown by the non-coaxial deformation of marbles layers (Fig. 9a). Some marble layers are affected by brittle normal faults, while others are boudinaged and separated by ductile shear zones rooting in the contact between Chroussa and Posidonia subunits. Whatever the regime of deformation and the physical conditions that prevailed, ductile or brittle, clear top-to-the east deformation is observed in the form of a thick shear zone (Fig. 9a). Below, the intensity of greenschist-facies retrogression increases in the vicinity of the shear zone, where metabasites are turned into chlorite-albite prasinites in which former HP-LT imprint is not detectable in the field. For example, west of Cape Achladi along the southern coast of the island, rocks of the Posidonia Subunit are strongly overprinted by greenschist-facies parageneses. At the cape, a metaconglomerate of Posidonia Subunit consisting of basic and calcitic pebbles embedded in heavily retrogressed metapelitic matrix crops out just below the contact. Within this metaconglomerate, pebbles are ductilely sheared with a top-to-the east kinematic (Fig. 9b). Structurally a few meters above, a ca. 20 m-long outcrop of preserved blueschist-facies metabasite is associated with eclogite boudins (Fig. 9c). This sharp transition from well-preserved blueschists and eclogites above strongly retrograded rocks below also supports the presence of a major shear zone between the Posidonia and Chroussa subunits, named in this study the Achladi-Delfini Shear Zone.

Furthermore, the same contact between Posidonia and Chroussa subunits is exposed around Delfini Bay that is bounded to the west by a small peninsula (Fig. 9d). Along a SW to NE transect through Delfini peninsula, two blue- to greenschist-facies shear zones are observed (Figs. 9d, 9e). Top-to-the east kinematic indicators such as shear bands, sigmoidal pressure shadows on garnets or drag folds associated with crystallization of syn-kinematic chlorite and albite are observed within the Delfini peninsula (Figs. 9f, 9g). These two metamorphic transition zones, distant of ca. 500 m, define the contact between Posidonia and Chroussa subunits. These shear zones have each accommodated a part of the total displacement and can be considered at large-scale as a single structure, the Achladi-Delfini Shear Zone (Fig. 3).

Despite poorer outcrop conditions within the island, the trace of this contact was followed by combining structural and metamorphic observations, looking especially for the preservation of HP-LT minerals. These field observations were strengthened by detailed analysis of aerial pictures. At map-scale, the resulting geometry of the Achladi-Delfini Shear Zone shows a sinuous contact extending over 13 km through the island (Fig. 3).

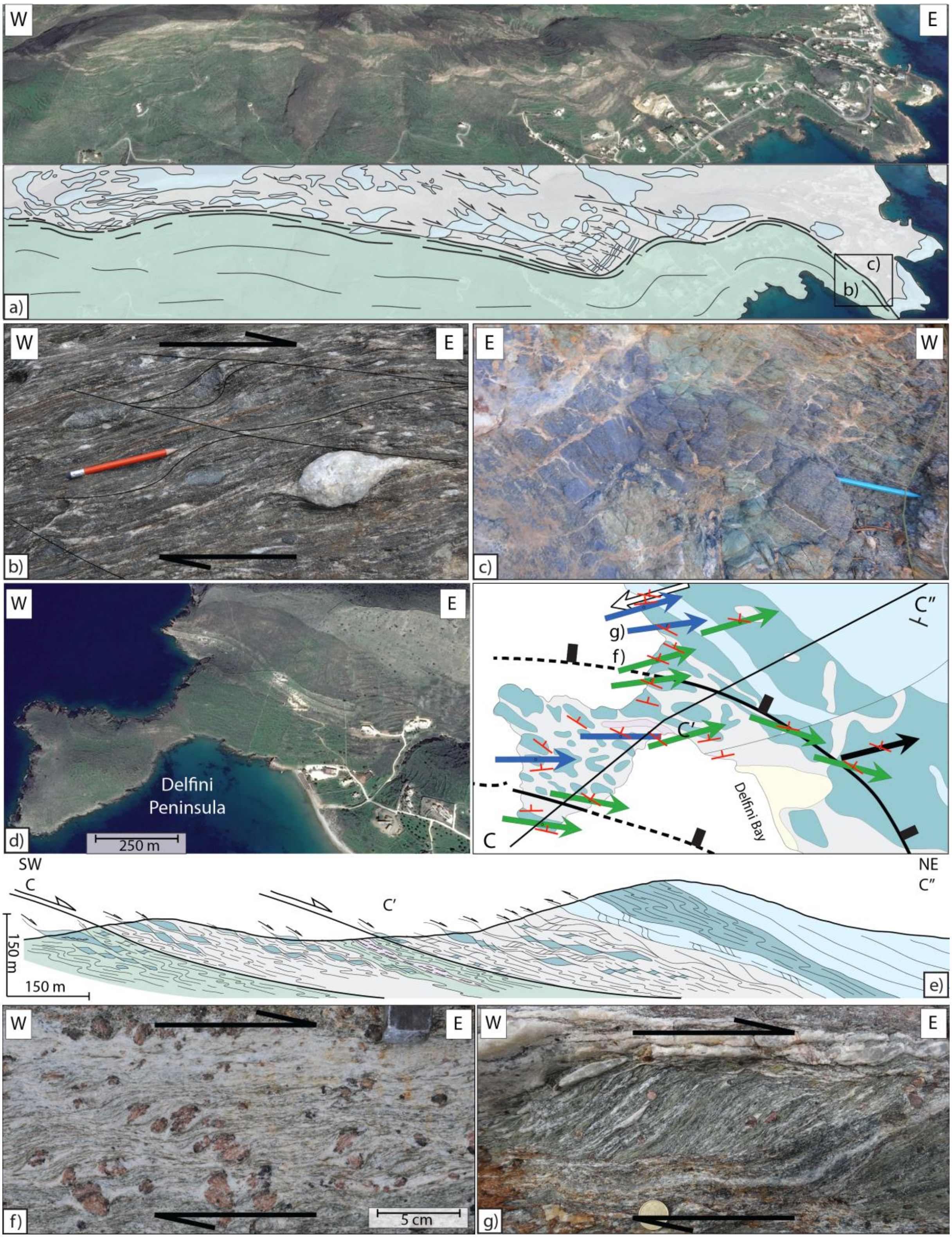


Figure 9: The top-to-the east Achladi-Delfini Shear Zone. a) Satellital image of the Achladi-Delfini Shear Zone observed above Achladi Cape and its interpretation showing top-to-the east sense of shear. b) Top-to-the east shearing in a greenschist metaconglomerate unit located just below the contact. c) Structurally few meters above, in the Chroussa Subunit, massive glaucophanites are observed with eclogitic boudins. d) Satellital image of the Delfini peninsula and its geological interpretation. e) Geological cross-section through the Delfini peninsula illustrating the architecture of the Achladi-Delfini Shear Zone. f) Top-to-the east kinematic indicators observed in retrogressed greenschist-facies rocks. g) Syn-blueschist top-to-the east shearing observed in the Chroussa Subunit.

5.2) Chroussa-Kampos subunits contact: the Kastri and Lia Shear Zones

The contact between Chroussa and Kampos subunits is well exposed in the northern part of the island, along the Kampos metabasite belt (Fig. 10; see also Keiter et al., 2004, 2011). This metabasic unit shows an E-W orientation and dips toward the north on the western side. It strikes more N-S dipping westward in its eastern half (Fig. 10). The northern and southern contact zones of the Kampos Subunit, i.e. the basal and roof contacts, are nicely exposed along the coast, especially on the way to Lia Beach (Fig. 10).

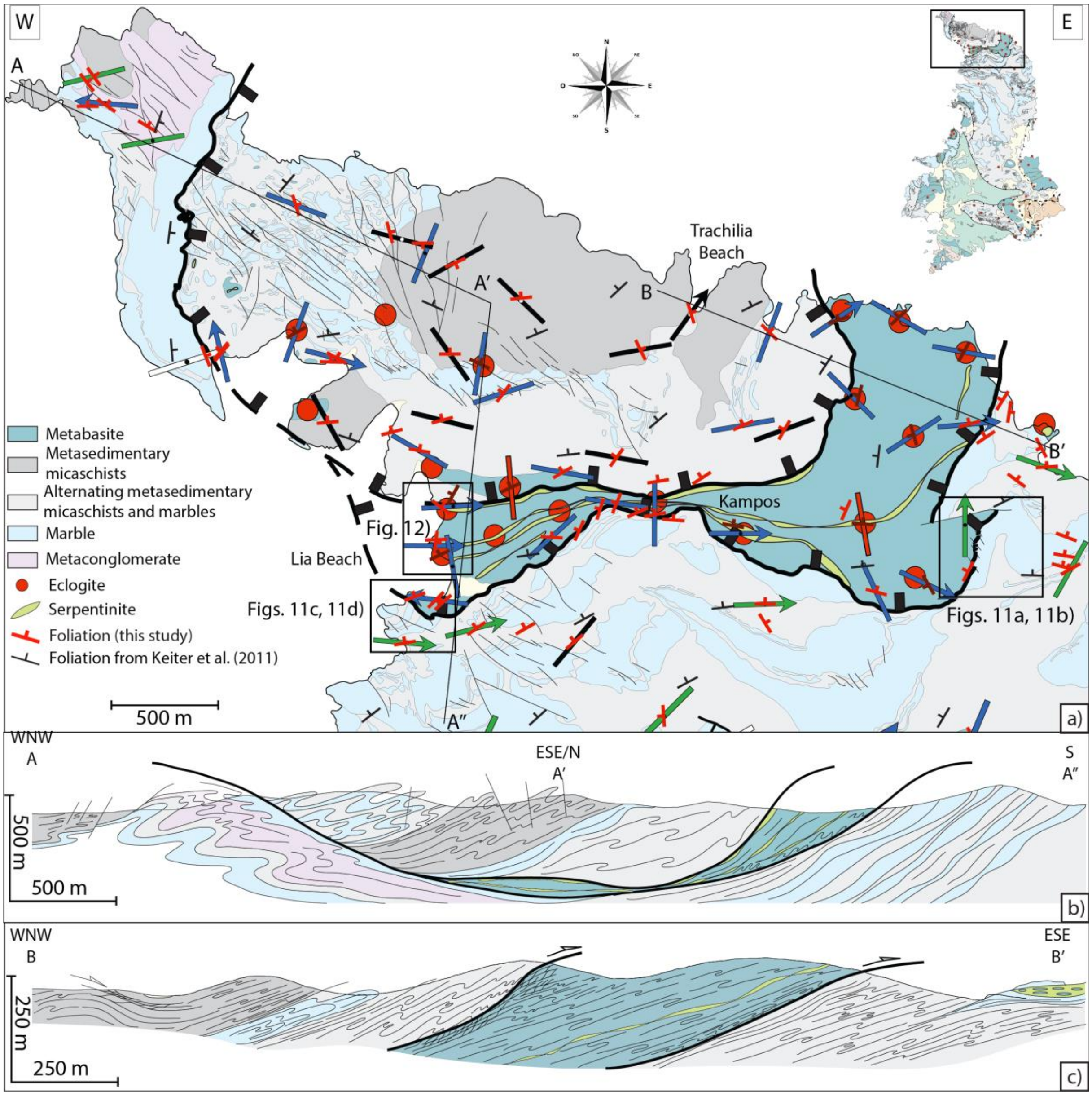


Figure 10: Geological architecture of the northern part of Syros. a) Geological map showing locations of cross-sections and figures 12 and 13. b) Cross-section illustrating the organization and deformation of structures. Note that large shear zones surround the western part of the Kampos metabasite belt. c) Detailed cross-section of the eastern part of the Kampos metabasite belt.

The basal contact of Kampos Subunit with Chroussa Subunit can be seen in the landscape near Kastri (Fig. 11a). At the contact, the marble layers of Chroussa Subunit are boudinaged and sheared, some of them showing large-scale sigmoids (Fig. 11a). These structures define a large-scale top-to-the northeast shear zone, named in this study the Kastri Shear Zone. Just below the contact, tightly folded marble intercalations occur as a result of intense shearing along this major shear zone (Fig. 11b). In contrast to the Kampos Subunit that preserved eclogite- to blueschist-facies parageneses, rocks of the Chroussa Subunit are strongly overprinted in greenschist-facies conditions all along the contact (Figs. 11c, 11d).

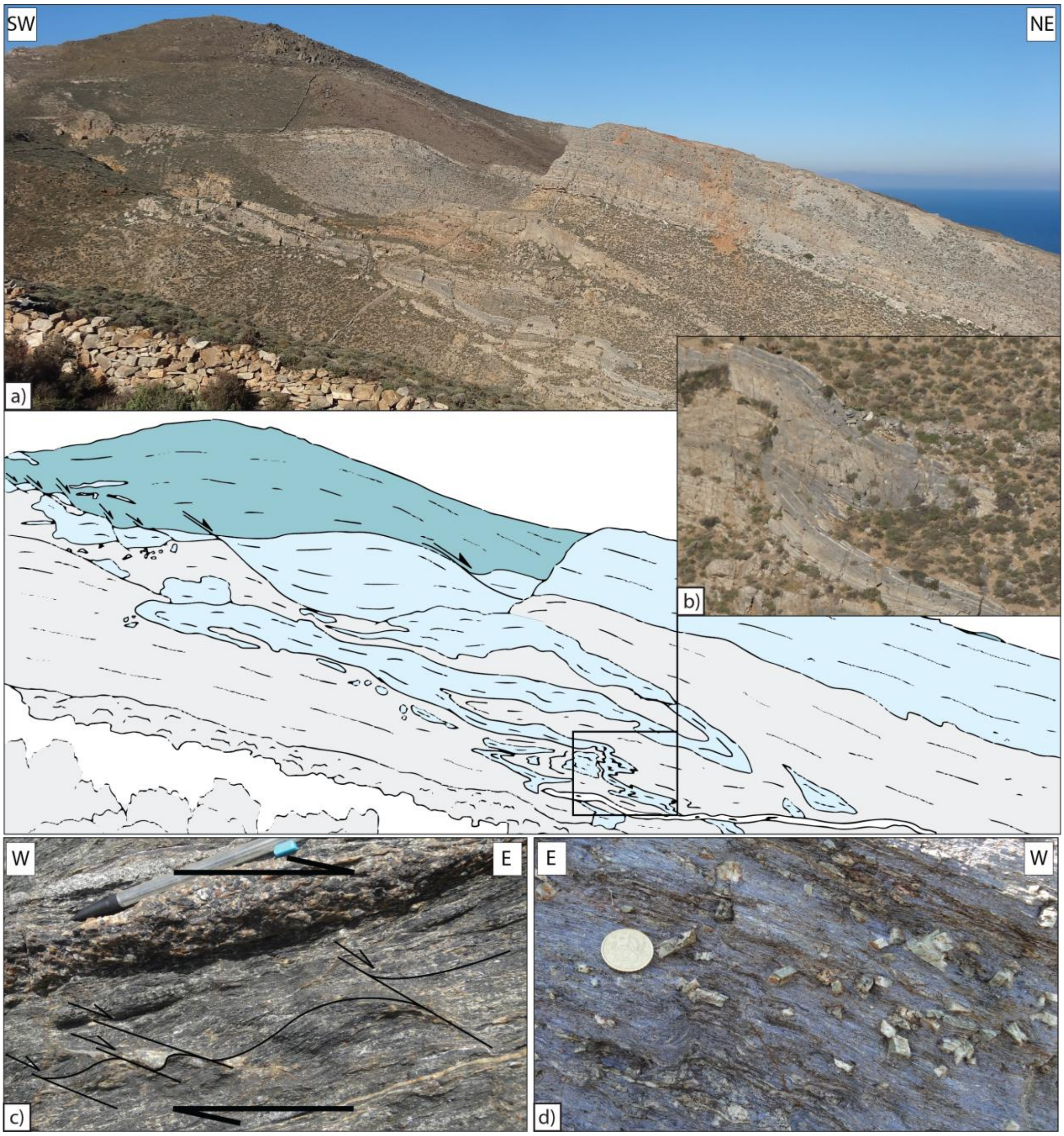


Figure 11: Basal contact of the Kampos metabasite belt: the Kastri Shear Zone. Pictures are located on the Fig. 12. a) Field view and its interpretation of the eastern part of the Kastri Shear Zone. Large-scale asymmetric boudins of marble are observed in the contact zone and show top-to-the northeast sense of deformation. b) Zoom showing the intense folding of black marbles below this contact. c) Directly below the contact, the Chroussa Subunit is highly retrogressed and displays syn-greenschist top-to-the east sense of shear. d) High-pressure glaucophanites bearing lawsonite pseudomorphs are well preserved up to the contact on Lia Beach.

Although the Kampos Subunit composes the upper structural part of the CBU, a klippe with a lithology similar to Chroussa Subunit is observed above the Kampos metabasite belt (Fig. 10). The contact zone between this klippe and the roof of the Kampos metabasite belt displays intense deformation and occurs between foliated serpentinite and metapelite (Figs. 12a, 12b). The foliation is parallel to the contact and is cut by a significant number of east-dipping shear zones decorated with syn-kinematic glaucophanes (Figs. 12b, 12c, 12d). This shear zone also shows asymmetrical boudins of metabasites included in a sigmoidal foliation compatible with top-to-the east shearing deformation and folds with curved axes mostly parallel to the stretching lineation, suggesting sheath folds (Figs. 12e, 12f). All these structures define the existence of a major syn-blueschist top-to-the east shear zone located at the roof of the Kampos metabasite belt, which we called the Lia Shear Zone.

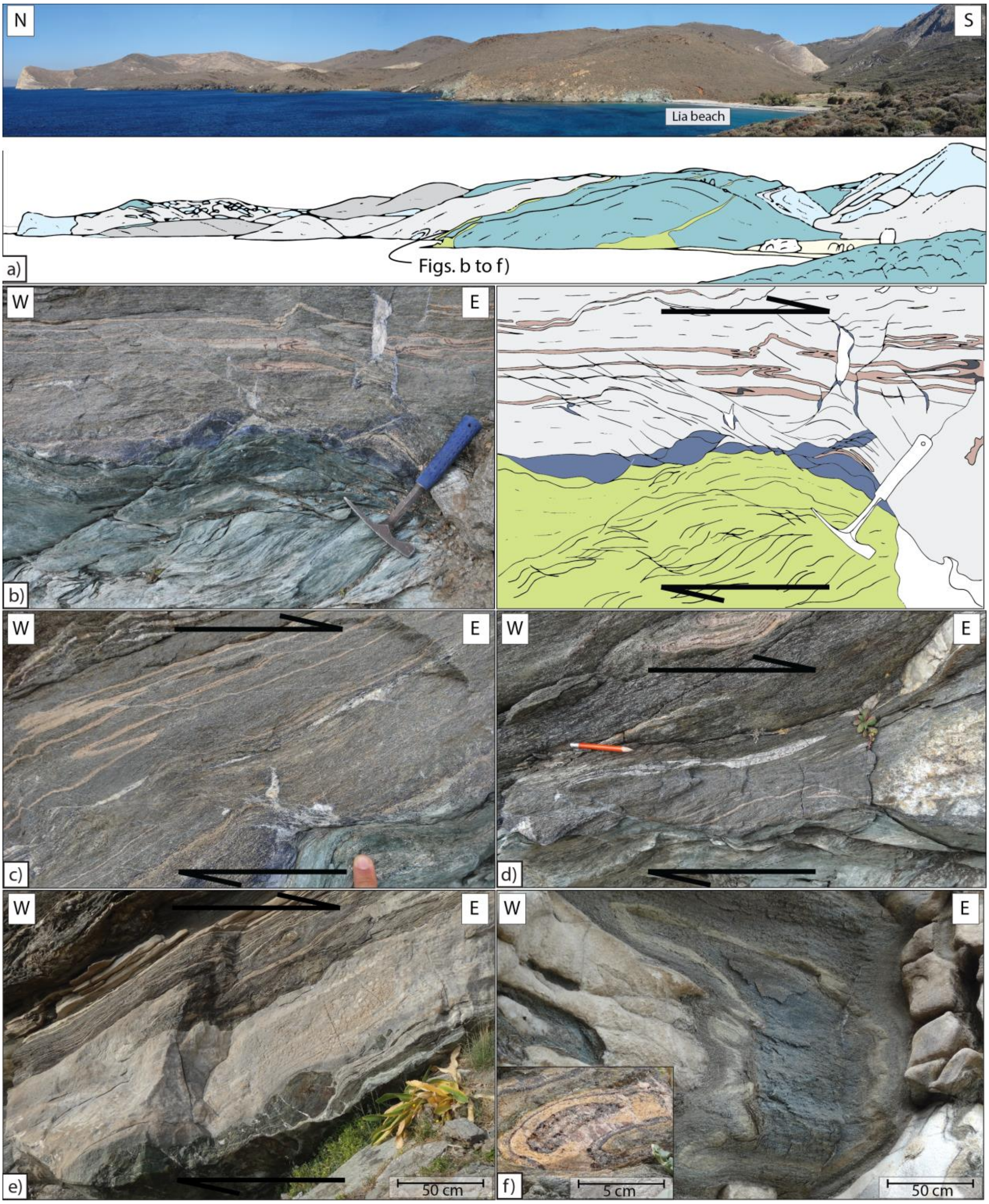


Figure 12: Roof contact of the Kampos metabasite belt. a) Field view of the western part of the Kampos metabasite belt and its geological interpretation. b, c, d) This contact is characterized by serpentinites below and metapelites on top, both affected by top-to-the east syn-blueschist shear bands. e) Asymmetric boudinage of a metabasite layer included in a sigmoidal foliation compatible with top-to-the east shearing deformation. f) Folds with curved axes sub-parallel to the stretching lineation and showing closed contour building the typical eye-structure of sheath folds.

5.3) CBU-Vari Unit contact: the Vari Detachment

The contact between the CBU and Vari Unit is a debated topic in literature. The contact itself is hidden by Quaternary deposits and probably affected by late normal faults. However, field investigations into the footwall unit, i.e. the CBU, allow proposing new arguments on the internal architecture of the Vari Detachment from bottom to top as it crops out from Cape Katerghaki to Vari (Fig. 13).

Below the contact, trending parallel to the stretching lineation, the whole section is characterized by a shallow northeast-dipping foliation showing that Vari Unit structurally overlain Kampos Subunit (Figs. 13a, 13b). As the rest of Kampos Subunit, these mafic rocks preserve HP-LT metamorphic parageneses such as eclogites and blueschists (see also Trotet et al., 2001a), and display a gradient of retrogression from eclogite- to blueschist-facies toward the contact. Indeed, the southwestern part of Cape Katerghaki (see location on Fig. 3) is composed of 10 m-thick massive eclogite bodies, which are more and more retrogressed in the blueschist-facies toward Vari Unit. All along this gradient, rocks show evidence of syn-eclogitic stretching reworked by syn-blueschists top-to-the east ductile shearing with HP-LT minerals such as glaucophanes decorating shear zones (Figs. 13c, 13d). South of Fabrika beach, structurally 20-30 m below the contact, a metaconglomerate composed of eclogitized mafic pebbles comprised within a marble matrix show top-to-the east sense of shear (Fig. 13e). Conjugate northeast-striking normal faults displace the inherited high-pressure structure by a few tens of meters. This may be due to conjugate normal faults (Figs. 13a, 13b).

Just above the contact and within the Vari Unit, mylonitic greenschists are observed, displaying only greenschist-facies metamorphism without any evidence of prior HP-LT stage, in contrast with the greenschist-facies metamorphic rocks observed in the bulk of the CBU. These rocks are strongly foliated and top-to-the E/NE shear criteria are observed such as sigmoidal pressure shadows on pyrite showing top-to-the east kinematic in the north of Fabrika beach, and top-to-the northeast shear bands south of Azolimnos village. On top of these greenschist-facies mylonites, the Vari orthogneiss shows a plano-linear ductile fabric with a stretching lineation oriented N70°E, intercalated in some places with fine-grained amphibolites. This unit is affected by brittle deformation, expressed as several 10 m-thick zones of cataclasites cutting through the orthogneiss (Fig. 13f; see also Soukis and Stöckli, 2013). Several E-W trending normal faults are observed in this area, cutting across the orthogneiss foliation at distance from the contact with the CBU, at variance with Philippon et al.'s (2011) interpretation of the regional structure. Our interpretation is confirmed at larger scale. Philippon et al. (2011) correlated the Vari basement lithologies with the so-called gneiss observed in the lower part of our Posidonia Unit, but we have seen that Posidonia Unit has seen the same peak of metamorphism as the other CBU of Syros with the local preservation of blueschists- or eclogite-facies metabasites while the Vari Unit has never been through HP-LT conditions.

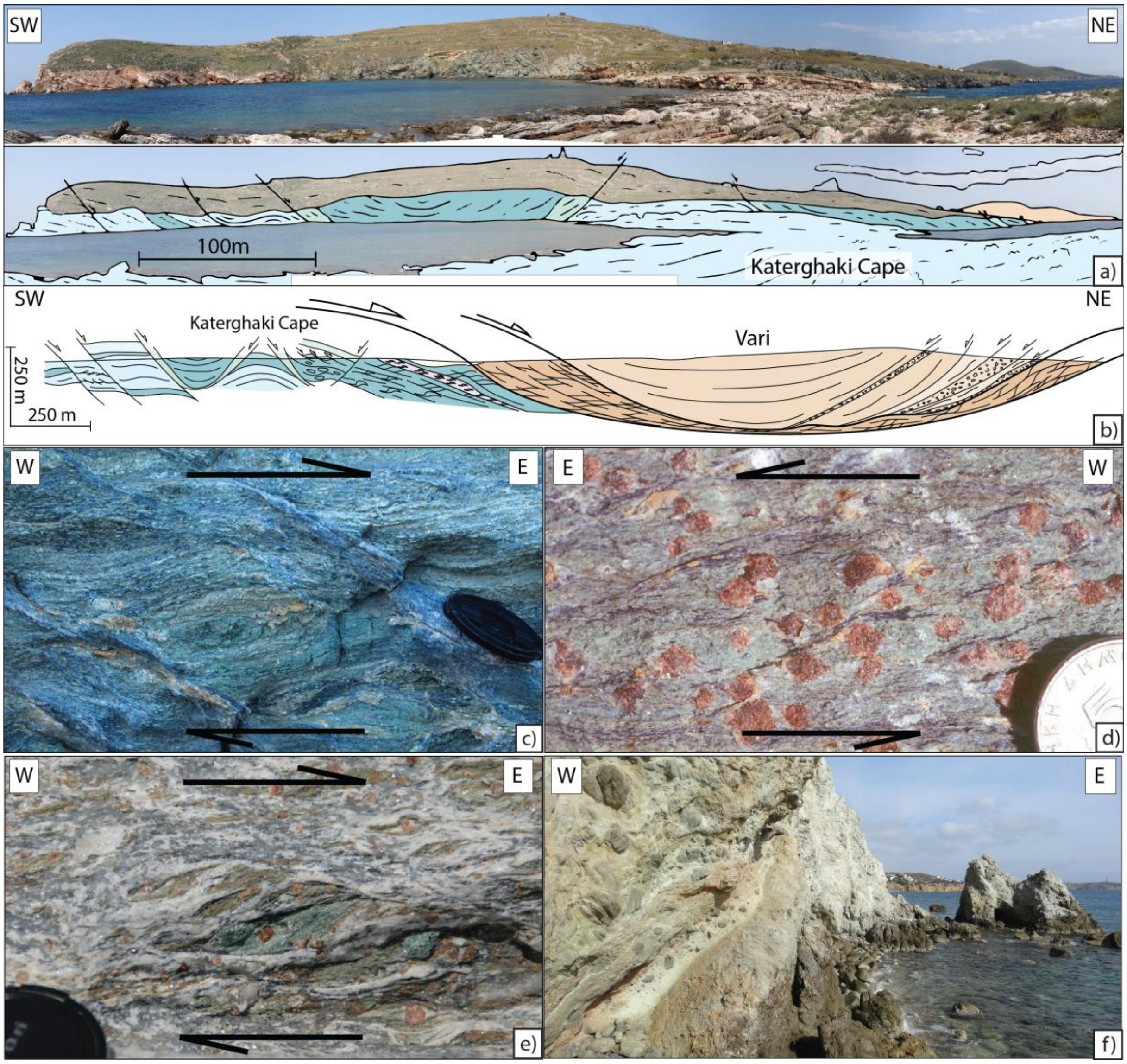


Figure 13: The Vari Detachment. a) Field photography showing that the CBU is structurally below the Vari Unit. b) Cross-section showing the architecture of the Vari Detachment and its top-to-the east sense of motion. c, d, e) Below the Vari Detachment, rocks of the CBU display a significant number of top-to-the east syn-blueschist shear bands affecting eclogites. f) Large-scale cataclastic zones observed upon the Vari Detachment within the gneiss of Vari.

6) Discussion

Although our new geological map matches the one of Keiter et al. (2011) from a lithological point of view, its structural interpretation is drastically different. This is particularly evident in the analysis of large-scale geometries, unit and subunit subdivisions and in the analysis of metamorphic record, which allowed us to identify several orders of shear zones due to strain localization.

6.1) What is left of the original nappe structure of the Cycladic Blueschist Unit?

We have recognized three distinct tectonic subunits composing the CBU in Syros, from top to base, the Kampos, Chroussa and Posidonia subunits, all resting structurally below the Vari Unit, which shows no evidence of HP. These subunits are characterized by their lithology and predominant metamorphic facies as seen in the field. All three subunits have seen the P-T conditions of the eclogite-facies but they have been subjected to different degrees of retrogression during exhumation. Following our observations, we propose a new metamorphic map based upon the study of predominant metamorphic facies, as well as on kinematic indicators and their relation to metamorphic parageneses (Fig. 14). This map, where colors correspond to the predominant metamorphic facies, displays the first-order distribution of the main parageneses.

The recognition of remains of eclogite within all three subunits implies that Kampos, Chroussa and Posidonia subunits have all undergone a HP-LT metamorphic event in the eclogite-facies. It ensues that local blueschist- or greenschist-facies rocks abundance is retrograde. The degree of retrogression, whether it occurred under blueschist and/or greenschist metamorphic conditions, is entirely different. Retrogression increases from top to bottom of the CBU, which points to important differences in the P-T-time evolution of the different subunits during exhumation, as previously proposed by Trotet et al. (2001b). The imprint of deformation during exhumation has been different in each of these subunits, intense in the lowermost Posidonia Subunit (where the entire subunit has been sheared and pervasively retrogressed), weaker in the uppermost Kampos Subunit (where blueschist- and then greenschist-facies deformation is localized along preferential shear zones). The Achladi-Delfini Shear Zone best shows this contrast. These features are similar to those observed on Sifnos (Roche et al., submitted) and seem characteristic of the large-scale structure acquired by the CBU within the subduction channel before those rocks were reworked by greenschist-facies deformation during Oligocene to Miocene extension. We now discuss the tectonometamorphic evolution of the subunits within the subduction channel.

The apparent inverse metamorphic gradient defined by the transition from the preserved high-pressure Kampos Subunit to the strongly retrograded Posidonia Subunit raises petrological questions. Indeed, very different P-T histories were so far published for Syros in terms of peak P-T conditions and shape of retrograde P-T path (Fig. 1b). Exhumation scenarios with a single retrograde P-T path for the whole CBU (Keiter et al., 2004, 2011; Schumacher et al., 2008) cannot explain the different degrees of retrogression observed in the CBU. Maximum P-T conditions around 15kbar and 500°C (Schumacher et al., 2008) just fringe the eclogite-facies (Fig. 1b) while eclogites are abundantly observed on Syros as well as on Sifnos (Trotet et al., 2001a). To justify these apparent contradictions, Schumacher et al. (2008) hypothesized that eclogites of Syros are the product of an earlier metamorphic event and were juxtaposed with the rest of the CBU by tectonic contacts. As result of our observations, the presence of eclogite boudins and lenses in all subunits cropping out on Syros, except the Vari Unit, does not fit the interpretation of Schumacher et al. (2008). An alternative explanation would be that the glaucophane-bearing marbles studied by Schumacher et al. (2008) were formed during the retrograde path in P-T conditions for which this assemblage is in equilibrium or that the amphibole mineralogy and stability is chemically buffered by the lithology. Indeed, much of the blueschist-facies parageneses on Syros are syn-kinematic and show top-to-the east sense of shear and clearly postdates the eclogite-facies. Consequently, our structural observations best fit the petrological analyses of Trotet et al.

(2001b), for whom all subunits of the CBU attained the same metamorphic peak in the P-T field of eclogite-facies, and followed different retrograde P-T paths, leading to different grade of retrogression in the CBU during the continuous activity of large-scale top-to-the east shear zones between Kampos, Chroussa and Posidonia subunits all over the exhumation (Fig. 1b). According to this interpretation, the tectonic history and the metamorphic path to the surface differ from the one envisaged by Keiter et al. (2004, 2011), who suggested rigid block exhumation mechanisms of the whole CBU as a single block. It remains true however that deformation progressively localized during exhumation along shear zones and that entire parts of the islands escape from the low-temperature deformation, these domains are those where the HP-LT parageneses are best preserved, as discussed in the next section.

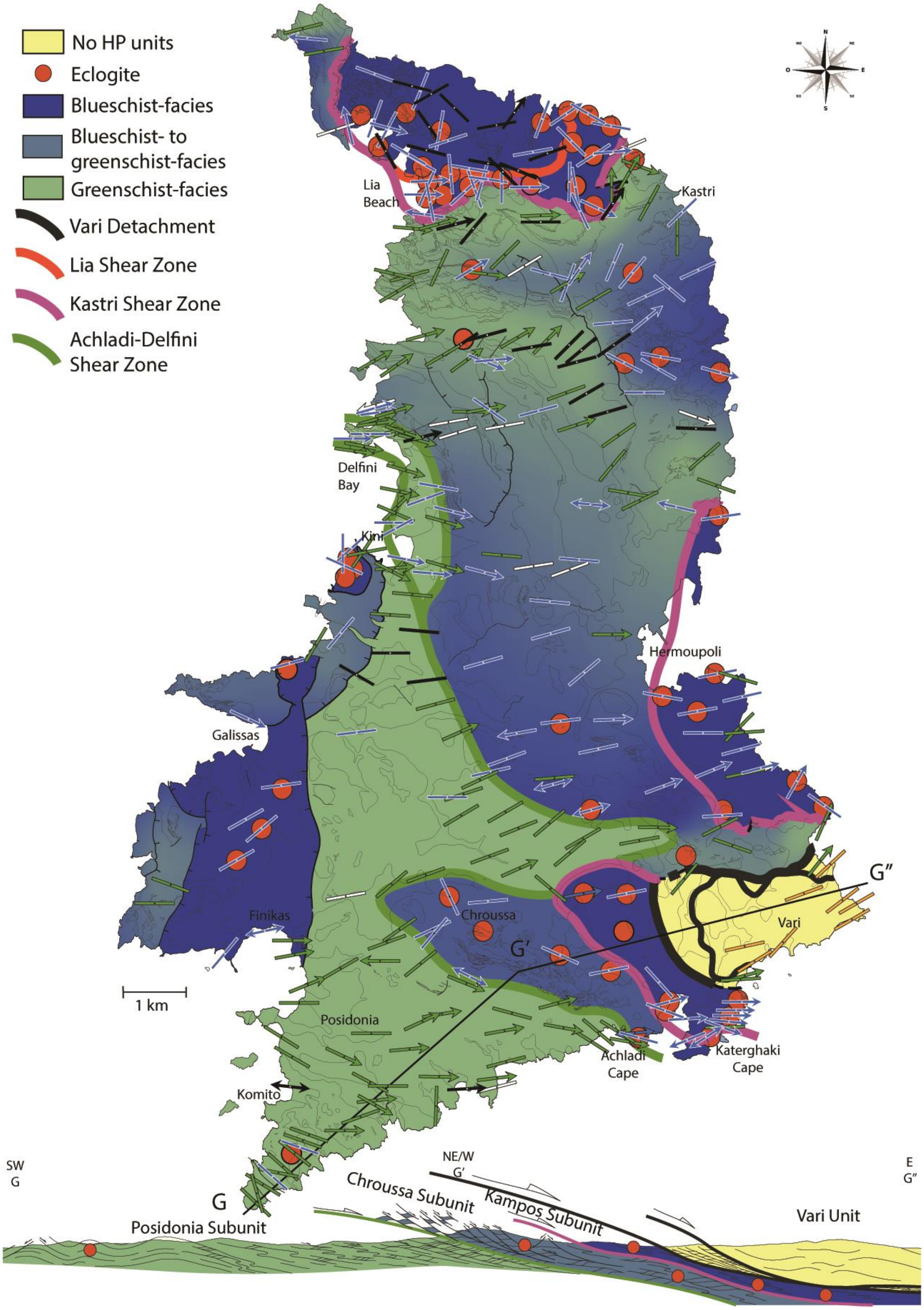


Figure 14: New metamorphic map of Syros showing an apparent inverse metamorphic gradient. The G-G'' cross-sections represent a synthetic view over the overall tectonometamorphic structure of Syros. The architecture of the CBU is subdivided here in three subunits separated by large-scale shear zones. Note that in our interpretation, the Vari Detachment juxtaposed with a top-to-the east motion the CBU and the uppermost Vari Unit.

6.2) Prograde or retrograde deformation?

A number of previous structural studies reported that prograde deformation is observed in Syros (Rosenbaum et al., 2002; Keiter et al., 2004, 2011; Philippon et al., 2011). Some of these studies postulated that this deformation took place just before or during peak metamorphism with no or only local retrograde deformation (Rosenbaum et al., 2002; Keiter et al., 2004, 2011). Three main arguments are presented in the literature. 1) The observation of deformed pseudomorphs of lawsonite: Philippon et al. (2011) noted that these pseudomorphs are always sheared with top-to-the S/SW kinematics and they correlated this sense of shear with subduction-related prograde thrusting. 2) The presence of large thrust zones, often described at the base of metabasic units. 3) The widespread preservation of aragonite pseudomorphs supports the view that no pervasive retrograde deformation occurred subsequently to the main prograde to peak metamorphism deformation event. The frequent presence of aragonite pseudomorphs in the Kampos Subunit, for instance in metaconglomerates, indeed shows that no significant deformation occurred at those places in the greenschist-facies and that parts of this subunit were exhumed as rigid bodies once they had exited blueschist-facies conditions (Schumacher et al., 2008).

Our study shows that the three subunits composing the CBU are each separated by top-to-the E/NE shear zones (Figs. 3, 14). This top-to-the E/NE deformation event observed within the entire volume of the CBU on Syros also affects lawsonite pseudomorphs (Fig. 6b) in contradiction with Philippon et al.'s observations (2011). Therefore, these structures are not only markers of prograde deformation, but also characterize early retrograde deformation. Indeed, taking into account the new lawsonite + glaucophane out reaction calculated for Fe-Mg end-member at X_{CO_2} = 0,01 (Schumacher et al., 2008), and the P-T path of Trotet et al.

(2001b), it appears that lawsonite could have been sheared with top-to-the east sense of shear during the first exhumation stages (Fig. 1b).

Geometry of the basal contact of the Kampos metabasite belt is quite complex and interpreted differently in previous studies. On one hand, Trotet et al. (2001a) describe this contact as a ductile detachment. For these authors, this contact is marked in the field by an apparent metamorphic gap between retrograded greenschist-facies rocks below the detachment and preserved eclogite- and blueschist-facies above (Fig. 2a). On the other hand, Keiter et al. (2004, 2011) and Philippon et al. (2011) described this contact as a large prograde thrust related to the subduction phase. Although Keiter et al. (2004) challenged the existence of a sharp metamorphic transition through this contact, we confirm this observation of Trotet et al. (2001a). Indeed, the contact zone is clearly marked by retrogression of the upper part of the underlying Chroussa Subunit over a 100 m-thick greenschist-facies shear zone. Moreover, all shear criteria observed within this shear zone are top-to-the E/NE, in agreement with syn-greenschist retrograde sense of shear observed within the Achladi-Delfini Shear Zone deeper down in the CBU. This does not preclude the possibility that the Kampos-Chroussa subunits contact is originally a thrust as it superimposes the Kampos Subunit, which is mostly ophiolitic, on top of the Chroussa Subunit, which is mostly made of metasediments. Our interpretation is that this thrust has been later reactivated as a major top-to-the east shear zone during exhumation. In the same way, we interpret the klippe of Chroussa Subunit, which is structurally positioned above the Kampos metabasite belt (Fig. 10), as thrusted onto the Kampos Subunit during the late prograde phase of subduction or during the early phase of exhumation. Indeed, this klippe corresponds lithologically to the Chroussa Subunit but shows only eclogite to blueschist parageneses as the Kampos Subunit (Fig. 14). Our observations show that this thrust was reactivated only in the blueschist-facies forming the Lia Shear Zone

(Fig. 12). Then the klippe and the Kampos metabasite belt may have followed, as a single unit, the same exhumation history.

In agreement with Trotet et al. (2001a), one of the major results of our study is the observation of a pervasive continuum of top-to-the E/NE deformation from P-T conditions of the metamorphic peak (eclogite-facies) to late stages of retrogression in the blueschist- and then greenschist-facies. In contrast to Rosenbaum et al. (2002), and Keiter et al. (2004, 2011), we conclude that a large part of the deformation in Syros was acquired during exhumation and that this deformation was heterogeneously distributed and preferentially localized along extensional shear zones.

However, it is also clear that locally, criteria of prograde or peak-metamorphism deformations are preserved. Different structures are most notably inconsistent with a pervasive top-to-the E/NE retrograde shearing. First, the orientation of stretching lineations is distinctly scattered in subunits best preserving eclogite and blueschist-facies parageneses (i.e. Chroussa and Kampos subunits; Figs. 3, 4). Indeed, a group of N-S oriented lineations and top-to-the S/SW kinematic indicators, already observed by Philippon et al. (2011), can be found in Kampos Subunit. Then, at a larger-scale, the N-S orientation of the Kampos metabasite belt (see Keiter et al., 2004, 2011) is inconsistent with E-W oriented deformation and top-to-the E/NE sense of shear. All these structures appear to be related with a N-S oriented shearing event and not with the retrograde top-to-the E/NE continuum of deformation described in this study. A plausible explanation would be that these structures were acquired during an early N-S oriented prograde event in the subduction channel, leading to formation of large thrust planes between units that are now found preserved in the highly metamorphic Kampos and Chroussa subunits. This interpretation is consistent with top-to-the S/SW prograde sense of shear described by Philippon et al. (2011). Such peak-metamorphic structures were later reactivated as weak contact zones during exhumation, within a top-to-the

E/NE non-coaxial regime progressively localizing strain toward the lower structural parts of the CBU. These features are discussed in the context of the heterogeneous localization of deformation during exhumation of the CBU.

6.3) Localization of deformation during exhumation

The roof contact of the Kampos metabasite belt is only marked by syn-blueschist deformation, showing that this shear zone was deactivated early in the exhumation process, and that the deformation localized progressively in the basal contact of Kampos Subunit, which is characterized by syn-greenschist deformation. In contrast with Posidonia Subunit, Chroussa Subunit is not totally retrogressed in the greenschist-facies and shows large portions characterized by the predominance of blueschist-facies parageneses. Once again, this feature illustrates the progressive localization of deformation during exhumation toward the base of the CBU, i.e. toward Posidonia Subunit. Finally, the Achladi-Delfini Shear Zone is currently characterized by syn-greenschist deformation that has overprinted the entire volume of Posidonia Subunit.

Progressive localization of deformation toward the base of the CBU in Syros during exhumation is linked with a younging of apparent ages towards the south, from Kampos (45-50 Ma, syn-orogenic period) to Posidonia subunits (20-35 Ma, post-orogenic period), especially shown by $^{40}Ar/^{39}Ar$ and Rb/Sr data on white micas (Fig. 2b; Maluski et al., 1987; Tomaschek, et al., 2003; Putlitz, et al., 2005; Huet, 2010; Bröcker et al., 2013). A possible explanation would be that structurally downward strain localization leads to partial resetting of isotopic systems or even recrystallization in the lowermost units. This migration of deformation could be enhanced by different factors such as intense fluid circulations in the basal part of the CBU and/or increased thermal influx at the base of the metamorphic pile

(Matthews and Schliestedt, 1984; Schliestedt and Matthews, 1987; Avigad, 1993; Trotet et al., 2001b). This localization could be also linked to the different lithologies composing the CBU on Syros, less and less resistant to deformation toward the base, passing from massive metabasite in Kampos Subunit to a succession of thick marble layers and metapelites in Chroussa Subunit and finally metapelites in Posidonia Subunit. During cooling of metamorphic units, this inherited rheological heterogeneity may have enhanced the downward localization of deformation toward the weak rheological units. So, while Posidonia Subunit has been deformed until the P-T conditions of the greenschist-facies, the Kampos Subunit and parts of the Chroussa Subunit have been only deformed during the first steps of exhumation. This participated to the local preservation of prograde markers of deformation seen today, allowing detailed petrological and structural information to be retrieved on the prograde subduction-related phase of deformation.

6.4) Thrusting, exhumation and extension

The contacts between Kampos, Chroussa and Posidonia subunits have a polyphase history. The first stage corresponds to the stacking of units by thrusting (i.e. nappe stacking), probably during the prograde evolution and at the pressure peak. A limited number of outcrops suggest that the sense of shear was toward the south during this first episode (Philippon et al., 2011). The main evidence of thrusting is that the uppermost HP-LT Kampos Subunit is mostly made of ophiolitic material, while the lowermost Posidonia Subunit is rich in metapelites that may have been deposited over a continental basement (Keiter et al., 2004; 2011; Schumacher et al., 2008; Philippon et al., 2011). In a second stage, the contacts were reactivated during the retrograde evolution and exhumation, via a top-to-the east shearing deformation, localized along the main contacts or distributed within the whole Posidonia

Subunit. This continuum of top-to-the east shear thus encompasses two major periods of the geodynamic evolution of the Aegean: (1) The Eocene construction of the Hellenides nappe stack and HP-LT accretionary complex of the CBU; (2) the Oligocene to Miocene extension leading to crustal thinning and formation of the Aegean Sea in the back-arc region of the Hellenic subduction. The first period corresponds to exhumation of the CBU within the subduction channel (syn-orogenic exhumation, Jolivet et al., 2003; Jolivet and Brun, 2010), and the second stage to the formation of metamorphic core complexes of the Cyclades (post-orogenic extension, Huet et al., 2011).

6.5) The Vari Detachment: an example of a subduction channel roof

Several studies describe the existence of the Vari Detachment on Syros, juxtaposing the Vari Unit above the CBU (Trotet et al., 2001a; Rosenbaum et al., 2002; Ring et al., 2003; Jolivet et al., 2010; Keiter et al., 2011; Soukis and Stöckli, 2013). It is also suggested that this detachment reappears on the neighboring island of Tinos (Maluski et al., 1987; Patzak et al., 1994; Jolivet et al., 2010; Soukis and Stöckli, 2013). This assumption is based on similar structural and metamorphic features of the footwall and hangingwall of the detachment outcropping in each island. On the other hand, Philippon et al. (2011) drastically revised the interpretation of this contact, repositioning the Vari Unit below the CBU. According to them, these rocks have to be correlated with the Cycladic Continental Basement cropping out in the southern part of the Cyclades (cf. Huet et al., 2009; Augier et al., 2015). On the contrary, we demonstrated here, that clear field evidences support the original interpretation putting the Vari Unit on top of the CBU (Figs. 13a, 13b). The Vari Detachment is generally considered as responsible for the exhumation of the CBU (Trotet et al., 2001a; Jolivet et al., 2010; Soukis and Stöckli, 2013). Trotet et al. (2001a, 2001b) and Jolivet et al. (2010) argued that the Vari

Detachment has accommodated part of the exhumation since the syn-orogenic period, whereas Ring et al. (2003) conclude that this structure only allowed the final exhumation of the CBU. Ring et al. (2003) obtained different retrograde cooling paths at the footwall and at the roof of the Vari Detachment with fission-tracks data on apatite and zircon gathered on Syros (Fig. 2b) and Tinos. From their results, they derive that intra-arc distributed extension caused only the final 6-9 km of vertical exhumation, and they conclude that the Vari Detachment was characterized by fast extension but caused little exhumation. But this detailed study is based upon fission-track data, which put only T-t constraints on the final parts of exhumation. Our structural observations show that the top-to-the E/NE deformation affecting the rocks located at the footwall of the Vari Detachment started in eclogite to blueschist P-T conditions and evolved progressively toward the conditions of the greenschist-facies. Cataclastic deformation observed in the Vari Detachment testifies that this detachment has continued to operate in brittle conditions, but not that this detachment started in brittle conditions as asserted by Ring et al. (2003). Huet et al. (2009) and Jolivet et al. (2010) hypothesized that the Vari Detachment represents the Eocene roof of the subduction channel. Then, with the Oligocene to Miocene southward slab retreat, the Vari Detachment was transferred in a back-arc position in the Late Miocene as attested by its present position.

6.6) Tectonometamorphic evolution of a subduction channel

Integrating the above presented and discussed new observations with the one available in literature, we propose a new tectonometamorphic evolution sequence. This scenario is divided in four steps:

1) From the early Paleocene (65 Ma) to the early Eocene (50 Ma):

From the end of the Cretaceous, the Apulian continental block subducted below the southern margin of Eurasia (Jolivet and Brun, 2010). During this N-S oriented subduction phase, the Hellenic nappe stack was progressively constructed. The Pindos oceanic domain probably started to subduct around 55 Ma (Menant et al., 2015) forming at depth the CBU (Bonneau and Kienast, 1982; Jolivet and Brun, 2010). Between 55 and 50 Ma, CBU rocks were strongly deformed, forming the observed N-S trending stretching lineation, resulting in the thrusting of subunits such as the Kampos Subunit with a resultant top-to-the S/SW sense of shear associated with prograde shear zones (Philippon et al., 2011) and large-scale open folds (Keiter et al., 2011; see also Roche et al., submitted, for Sifnos Island).

2) From the early Eocene (50 Ma) to the early Oligocene (35-30 Ma):

The CBU started to exhume, following an initial cold retrograde P-T path able to preserve HP-LT parageneses. Ductile shear zones associated with syn-blueschist top-to-the east sense of shear accommodated this exhumation below the Vari Detachment that represented the roof of the subduction channel. During this syn-orogenic phase, deformation started to localize at the interface between large lithological units, probably along former thrusts, delimiting the subunits detached from the overlying plate. During this period, a top-to-the south thrust, observed on Ios Island and located at the base of the CBU (Huet et al., 2009), was active and exhumation of the CBU was accommodated within the subduction channel of a slowly retreating subduction zone while the thrust front was propagated southward (Jolivet et al., 2003; Brun and Faccenna, 2008, Jolivet and Brun, 2010; Ring et al., 2010).

3) From the early Oligocene (30-35 Ma) to the early Miocene (23-19 Ma):

A drastic change in kinematic boundary conditions occurs at 30-35 Ma with a decrease of the absolute northward motion of Africa and the southward retreat of the subducting slab (Jolivet and Faccenna, 2000). This drastic change marks the transition from syn-orogenic exhumation to post-orogenic extension and the formation of the Aegean Sea. The post-orogenic extensional regime is still characterized by top-to-the E/NE sense of shear as observed in the Achladi-Delfini Shear Zone. During exhumation, deformation progressively localized in lower structural levels of the CBU where retrogression is almost complete.

4) From the Early Miocene (23-19 Ma) to the present:

The final exhumation of the CBU is first controlled by ductile-brittle normal faults and finally by purely brittle normal faults. The Achladi-Delfini Shear Zone displays ductile-brittle deformation with top-to-the E/NE sense of shear, like some outcrops in the Chroussa Subunit. Large-scale brittle normal faults can finally affect the exhumed units such as the 4 km Finikas-Galissas Fault, which juxtaposes well-preserved eclogite- to blueschist-facies rocks with strongly retrogressed units (Figs. 3, 8b).

7) Conclusion

In this study, new geological and metamorphic maps and cross-sections of Syros have been proposed, described and discussed. Field mapping combined with structural and petrological observations allow us to subdivide the CBU into three subunits, Kampos, Chroussa and Posidonia subunits, separated by major ductile shear zones. Eclogite is found within all three subunits. This implies that, despite their entirely different degree of retrogression (from eclogite at the top to greenschist at the base), the subunits have undergone the same HP-LT metamorphic peak in eclogite-facies, pointing to important differences in P-T-time evolution during exhumation. Large-scale ductile shear zones delimiting the subunits record a multi-stage structural evolution. They may have formed during burial with the development of a currently N-S trending eclogite to blueschist stretching lineation accompanied by top-to-the S/SW sense of shear. From the P-T conditions of the metamorphic peak and during exhumation, the contacts were reactivated as top-to-the east ductile extensional shear zones. New observations of the Vari Detachment, which juxtaposes the low-pressure Vari Unit onto the CBU, show consistent top-to-the-east shear sense. We infer that, after the prograde top-to-the S/SW deformation, the CBU was exhumed by an overall top-to-the east shearing all the way from the depth of the eclogite-facies to the greenschist-facies and finally, into the brittle crust. During exhumation, deformation progressively localized downward in the CBU, along several large-scale ductile shear zones, allowing preservation of earlier HP-LT structures and metamorphic parageneses.

This study brings new insights on the tectonometamorphic evolution of a subduction channel, showing progressive strain localization, during both the prograde and retrograde history. The rate of this progressive strain localization is however unknown, and in general, poorly known in similar geological contexts. Are all shear zones coeval, do they work at the same time or can we see a sequential development until final localization on the brittle Vari Detachment? As an open question left for further work, we can say that modeling the evolution of the CBU accretionary complex and understanding the mechanical behavior of the subduction interface requires quantifying the rate of strain localization. Acquisition of detailed time constraints along the P-T path is fundamental in determining the role and the importance of the shear zones bounding the subunits of Syros, it is a pre-requisite for further considerations on exhumation mechanisms.

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